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Climate-smart Actions in the Operating Theatre for Improving Sustainability Practices: A Systematic Review

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Abstract

Context: Surgical activity contributes to global warming though the production of greenhouse gases and consumption of resources. To date, no clinical practice guidelines have been made to promote and implement climate-smart actions.
Objective: To perform a systematic review of the available actions that could limit CO_2 emission in the operating room (OR) and their potential benefits upon the environment, whilst preserving quality of care.
Evidence acquisition: MEDLINE and Cochrane databases were searched from January 1, 1990 to April 2021. We included studies assessing carbon footprint (CF) in the OR and articles detailing actions that limit or reduce CF.
Evidence synthesis: Thirty-eight studies met the inclusion criteria. We identified six core climate-smart actions: (1) waste reduction by segregation; (2) waste reduction by recycling, reuse, and reprocessing; (3) sterilisation; (4) anaesthesia gas management; and (5) improvement of energy use. Quantitative analysis regarding the CF was not possible due to the lack of homogeneous data. For climate-smart actions, the analysis was limited by discrepancies in study scope and in the methodology of CO_2 emission calculation. Improvement of education and awareness was found to have an important impact on waste segregation and reduction. Waste management is the area where health care

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workers could have the strongest impact, whereas the main field to reduce CF in the OR was found to be energy consumption.

Conclusions: This review provides arguments for many climate-smart actions that could be implemented in our daily practice. Improving awareness and education are important to act collectively in a sustainable way. Further studies are mandatory to assess the impact of these climate-smart actions in the OR.

Patient summary: We performed a systematic review of the available scientific literature to reference all the climate-smart actions proposed to improve the sustainability of surgical activities. Waste segregation, waste reduction and recycling, reuse and reprocessing, sterilisation, anaesthesia gas changes, and improvement of energy use in the operating room were found to be the main areas of research. There is still a long way to go to homogenise and improve the quality of our climate-smart actions.

1. Introduction

In 2015, during the 21st United Nations Conference of the Parties on Climate Change COP21 in Paris, 196 delegations decided to reduce their greenhouse gas (GHG) emission (definition in Table 1) to avoid a global temperature increase of >2°C by 2050 [1]. Global health would be threatened by the worldwide human-induced global warming [2]. In this context, the United Nations also adopted in 2015 the Sustainable Development Goals to end poverty, protect the planet, and enhance human lives [3]. Good health and well-being are the third goal, and measures to reduce global warming should ensure that health care remains accessible for people in all countries. Consequently, many countries should still reduce their GHG emission by around five times [4]. Indeed, the GHG emission reduction objective varies between countries as some already reached carbon neutrality (Bhutan and Suriname), some initiated the reduction (>50% of GHG emission reduction in Europe and the USA), and some did not initiate the process yet (China). Among

Table 1 – Lexicon of common terms in climate-smart actions

Definition of common terms used to understand climate-smart actions	
Greenhouse gas emission	Greenhouse gases (GHGs) are the gases that trap heat in the atmosphere. The main gases are carbon dioxide (CO_2), methane, nitrous oxide, and fluorinated gases.
Carbon footprint	Carbon footprint is usually expressed as a measure of weight, as in tons of CO_2 or CO_2 equivalent (CO_2e) per year. It is defined by the quantity of GHGs expressed in terms of CO_2e, emitted into the atmosphere by an individual, organisation, process, product, or event from within a specified boundary. It includes direct emission, such as that resulting from fossil-fuel combustion in manufacturing, heating, and transportation, as well as emission required to produce the electricity associated with goods and services consumed. In addition, the carbon footprint concept also often includes the emission of other GHGs, such as methane, nitrous oxide, or chlorofluorocarbons.
CO_2 emission	CO_2 enters the atmosphere through burning fossil fuels (coal, natural gas, and oil), solid waste, trees, and other biological materials, and also as a result of certain chemical reactions. CO_2 is the primary GHG emitted through human activities.
CO_2 equivalent	CO_2e is a unit of measurement that is used to standardise the climate effects of various GHGs.
Low-carbon power	Low-carbon power is electricity produced with substantially lower GHG emission than conventional fossil fuel power generation. It is one of the most important actions required to limit climate change. It includes wind power, solar power, nuclear power, and hydropower.
Cradle to grave	This is a complete assessment of the product life cycle. It includes all the steps from the resource extraction (cradle) to the use and disposable phases (grave).
Cradle to gate	This is a way to assess a part of the product life cycle from resource extraction (cradle) to the factory gate (ie, before it is transported to the consumer). The cradle-to-gate assessment does not include the use and disposable phases of the product.
Scopes of GHG emission	The ISO 14064 standard categorises GHG emission into three separate scopes: 1. Scope 1: Direct GHG emission from sources that are owned or controlled (direct emission from stationary combustion, mobile combustion, direct process-related emission, and direct fugitive emission [leaks and other irregular releases of gases or vapours from a pressurised containment]). 2. Scope 2: Indirect energy GHG emission are those that come from the consumption of imported electricity and from consumed energy imported through a physical network (steam, heating, cooling, and compressed air). 3. Scope 3: Other types of indirect GHG emission are consequences of the activities of organisations, such as purchased products, capital equipment, waste generated from organisational activities, upstream transport, upstream leased assets, patient and healthcare worker transports, downstream transport, use phase of the product, and lifecycle of the product.
Climate-smart actions	These are opportunities to adapt to the impacts of climate change and mitigate GHG emission. The objective is to sustainably increase productivity, adapt and build resilience to climate change, and reduce or remove greenhouse gases.
Sustainability	This is meeting the needs of the present without compromising the ability of future generations to meet their own needs. Sustainability is broken into three core concepts: economic, social, and environmental. "Environmental sustainability" is the responsibility to conserve natural resources and protect global ecosystems to support health and well-being, now and in the future.
Waste segregation	Waste segregation is the sorting and separation of waste types to facilitate recycling and correct onward disposal. It remains a key to waste minimisation and is essential for effective waste management.
Recycling	This includes actions that consist of converting waste materials into new materials.
Reprocessing medical device	This includes actions that consist of the disinfection, cleaning, remanufacturing, testing, and sterilisation (among other steps) of a medical device to be put in service again.
Domestic waste	This comprises all uncontaminated medical and nonmedical waste that are not at risk of infection transmission.
Regulated medical waste	This is also known as "biohazardous" waste or "infectious medical" waste. This is the portion of the waste stream that may be contaminated by blood, body fluids, or other potentially infectious materials, thus posing a significant risk of transmitting infection.

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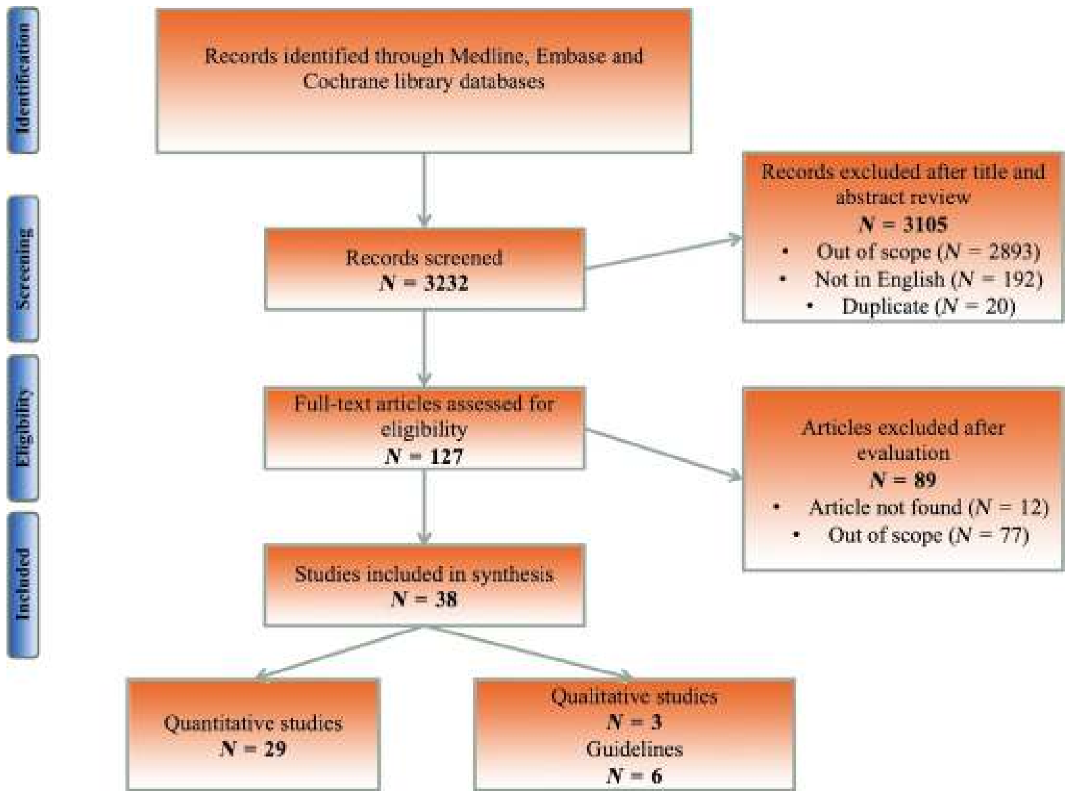

Fig. 1 – PRISMA flow-chart. PRISMA = Preferred Reporting Items for Systematic Reviews and Meta-analyses.

the GHGs emitted, the health care sector is estimated to be responsible for 10% of total emission in the USA and 20% of public sector emission in the UK [5,6]. Overall, health care's climate footprint is equivalent to 4.4% of global net emission, with various discrepancies between countries [7]. The performance of today's surgical efficiency relies on energy, human resources, fluids, materials such as disposables and innovative technologies, and sterilisation procedures that have a high environmental impact [8]. Indeed, the surgical unwitting contribution to the problem is considerable; for instance, a recent study evaluating annual GHG emission of operating rooms (ORs) from three different geographical countries and health care systems reported annual GHG emission of between 3000 and 5000 tons of CO_2 (as a comparison, worldwide agriculture and fishing release 850 million tons of CO_2) [9].

Although many organisations and health care workers initiated intuitive climate-smart actions [10–12], the relative environmental effect of these actions remains unclear, and the awareness of the medical and surgical community on the best climate-smart actions seems to be weak as there are limited data in the literature [13]. These issues could have an adverse impact on the implementation of future greening programme in the OR.

Climate emergency requires significant leadership with efficient and significant actions. Indeed, developing low carbon sustainable health care systems is one of the aims of the 2021 COP26 [11]. Therefore, in this systematic review, we aimed at providing an overview of the strategies for conducting climate-smart actions in the operating theatre and their potential magnitude in reducing OR GHG emission, whilst preserving the quality of care.

2. Evidence acquisition

A systematic literature review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) [14]. The protocol was registered on PROSPERO (no. CRD42021240371).

2.1. *Search strategy and study selection*

A systematic search of the MEDLINE via PubMed and Cochrane databases was performed in April 2021. Only articles published in English or French were searched. The keywords used for the search strategy are listed in the Supplementary material. All relevant guidelines from scientific societies or governments and grey literature sources were also searched. Two reviewers (B.P. and U.P.) independently screened all abstracts and full-text articles of all retrieved studies. At each selection step, disagreements between the two reviewers were solved by discussion, and, in case of no agreement, a third party was involved in the study selection process.

We included all qualitative and quantitative studies reporting methods that could reduce the environmental impact within the OR. In detail, we included studies assessing the carbon footprint (CF) and studies on main actions for limiting or reducing the CF, namely, studies on waste management, sterilisation, recycling, and reprocessing as well as

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Table 2 – Description of studies included

Study	Type of study	*N*	Outcome	Main results
Francis et al [22]	Quantitative Prospective	NA	Evaluation of mishandled noninfectious waste in OR during 3 wk Evaluation of the effect of separate colour bags on the management of noninfectious waste	7.5% mishandled waste 30% increase of noninfectious waste with colour bags
Lee and Mears [23]	Quantitative Prospective	20 orthopaedic procedures	Evaluation of mishandled noninfectious waste in OR	30% of OR waste was mislabelled as "infected waste"
Hubbard et al [24]	Quantitative Prospective	51 procedures	Evaluation of the medical waste reduction using separate bags for surgery and anaesthesia	Median weight = 0.35 kg/procedure
Burbridge et al [25]	Quantitative Prospective	NS	Evaluation of the discarding of CO_2 absorbers as solid waste	Decrease of waste 2.8 tons/yr
Agrawal et al [26]	Quantitative Survey	1135 responders	Evaluation of appropriateness of disposal methods	65% mishandled regular trash 98% reported lack of information
Ard [27]	Quantitative Survey	2189 anaesthesiologists	Evaluation of environmental sustainability	80.1% interested in recycling 27.7% recycle in their OR 67% have not sufficient education
Martin et al [28]	Quantitative Prospective	16 OR	Evaluation of a waste stream optimisation programme with waste bag weight assessment	12% decrease of solid bag waste 59% decrease of medical bag waste 19% increase of recycled material
Wyssusek et al [29]	Quantitative Prospective	21 OR	Evaluation of a waste segregation and recycling programme	82% decrease of clinical waste produced 60% decrease waste disposal costs
Denny et al [30]	Quantitative Prospective	2 OR	Evaluation of unused endotracheal tubes and disposable laryngoscope blades after an educational programme	63% decrease of endotracheal tubes 54% decrease of laryngoscopes blade
Wormer et al [31]	Quantitative Prospective	NA	Evaluation of a "green OR campaign"	75% red bag waste 234 tons of CO_2 emission
McKendrick et al [32]	Quantitative Audit	20 surgical procedures	Evaluation of GHG emission saved thanks to recycling	54 kg recycled 25 kg CO_2 emission saved
Lui et al [33]	Quantitative Prospective	97 surgical procedures	Evaluation of potential preoperative uncontaminated waste	21% of operating waste could be recycled
Lee and Mears [34]	Quantitative	NA	Evaluation of an OR greening programme	5 tons/yr reduction of blue wrap consumption 50% decrease of annual waste output
Misrai et al [35]	Quantitative	7 disposable minimally invasive surgical devices in urology	Estimation of CO_2e emission of urological disposable surgical devices	Carbon footprint varied between 0.07 and 3.3 kg CO_2e Between 9% and 86% was attributed to packages and user manuals
Thiel et al [36]	Quantitative Prospective	17 laparoscopic hysterectomies	GHG decrease	25% with desflurane removal 10% with reusable instruments 5% with recycling waste
Babu et al [37]	Quantitative	10 OR	Environmental impact of blue wrap recycling during 39 d	555 kg recycled 158 700 kWh saved
Azouz et al [38]	Quantitative Survey	524 participants	Evaluation of barriers to recycling and perception of waste in the OR	57% cannot differentiate recyclable waste 48% lack of education
Petre et al [39]	Quantitative Survey	426 anaesthesiologists	Evaluation of attitude towards and barriers regarding recycling in the OR	97.5% willing to recycle 30.3% recycle in the OR 63.5% reported lack of support from OR leadership 62.8% reported inadequate education
McGain et al [40]	Quantitative Survey	780 anaesthesiologists	Evaluation of views of OR recycling	93% wants to increase recycling 11% agreed that recycled already occurred in their OR Greatest barriers to recycling were (1) inadequate facilities (49%), (2) negative staff attitude (17%), and (3) inadequate education (16%)
Conrardy et al [41]	Quantitative Survey	172 surgeons and surgical technologists	Evaluation of using reusable surgical basins, gowns, and table stand covers	The majority preferred reusable products 65% decrease of regulated medical waste
McGain et al [43]	Quantitative Retrospective	NA	Evaluation of CO_2 emission when converting from single-use equipment to reusable anaesthetic equipment in different continents	480 kg CO_2e increase (9%) in Australia 4873 kg CO_2e decrease (84%) in Europe 2427 kg CO_2e decrease (48%) in the USA
McGain et al [44]	Quantitative Retrospective	NA	Life-cycle assessment of reusable and single-use central venous catheter kits	Reusable kit emitted 1211 g of CO_2 versus 407 g for single-use kit
Davis et al [45]	Quantitative	NA	Comparison of CO_2 emission between single-use and reusable flexible ureteroscopes	4.43 kg of CO_2 per case for single-use versus 4.47 kg of CO_2 for reusable
Sherman et al [47]	Quantitative	NA	Life-cycle assessment of reusable and single-use laryngoscope	Single-use plastic laryngoscope emitted 16–18 more CO_2e than reusable the one with steel handle
Kozarek et al [50]	Quantitative In vitro	10 sphincterotomes	Evaluation of single-use sphincterotome reprocessing	No residual organism after sterilisation 7 (70%) remained intact after 8 uses
Roth et al [51]	Quantitative Prospective	NS	Evaluation of cleaning, sterilisation, and disinfection of single-use device using current standards	100% remained contaminated after cleaning and sterilisation
Adler et al [54]	Quantitative Retrospective	225 procedures/yr during 5 yr	Comparison of environmental impact between disposable and reusable laparoscopic instruments	5249 kWh of energy for sterilisation consumption of reusable 812 kg of waste generated by single-use instruments

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Table 2 (*continued*)

Study	Type of study	*N*	Outcome	Main results
Tempia et al [56]	Quantitative Prospective randomised	81 patients undergoing major surgery	Evaluation of an anaesthetic conservative device that vaporises sevoflurane under different fresh gas flow conditions	Sevoflurane consumption was significantly reduced with low-flow circle system
Lin et al [60]	Quantitative	NA	Evaluation of a radiofrequency identification system to automatically control high-efficiency particulate air in the OR	50% of energy saving in the OR with this system

GHG = greenhouse gas; NA = not available; NS = not specified; OR = operating room.

the ecological impact of reusable/disposable devices (Table 1). According to the PICO framework, we included all the studies that were related to actions that take place in the OR (Population) and that assessed any climate-smart actions that aimed to improve the sustainability of surgical activities (Intervention), there was no comparator provided, and we collected all variables that objectively reflect the climate-smart actions including CO_2 equivalent (CO_2e), GHG emission, weight of waste, etc. (Outcomes). All studies that did not report specific endpoints, such as CO_2 emission or not at the level of the OR, were excluded from this systematic review.

3. Evidence synthesis

We identified 3232 citations, of which 127 required full-text review after title and abstract screening, and 38 studies met the inclusion criteria after full-text reading (Fig. 1). Among them, six were guidelines, three were qualitative studies, and 29 were quantitative studies (Table 2). Nevertheless, due to the heterogeneity of the endpoints used among studies, a quantitative analysis of the pooled data was not feasible. Therefore, after reviewing all selected articles, it was decided by a common agreement among authors to report the results in a comprehensive way.

3.1. *General concept to reduce CF in the OR*

The fundamental principles of reducing waste in the OR are based on the cornerstone strategy of waste minimisation and rely on the principles of "three Rs": reduce, reuse, and recycle [15]. This programme was developed by the University of Virginia Health Sciences Center and aimed at reducing medical waste. It outlines the "blueprint" for the three R's project and includes recommendations for identifying and handling infectious, clean, and clean/reusable waste [15]. More recently, experts have suggested the addition of two Rs: rethink/research and renewable energies [16] that have also been implemented and assessed in the OR [17,18].

Any action with the intent to improve the environmental impact of activity in OR should always consider the different aspects of eco-friendly behaviour, which is based on the 5R rules (Fig. 2):

Fig. 2 – Climate-smart actions proposed in the literature. OR = operating room.

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1. Reduce (ie, proper waste segregation, reusable sharps container, fluid waste management, energy expenditure, LED surgical lamps, greener equipment packaging, and reduce the use of OR).
2. Reuse (ie, reprocessing of single-use devices and reusable surgical linens).
3. Recycle-renew (ie, recycle plastic and paper waste, transformation of plastic and paper, or reprocessing medical devices).
4. Rethink/research (ie, life cycle analyses of materials, cost comparison of technologies, and development of "green" devices).
5. Renewable energies (ie, photocatalytic membrane reactors to degrade cytostatic drugs, electrochemistry methods, microbial strains with different oxygen requirements, and biogas for heat and power production).

3.2. *Improve segregation*

Nine studies reported that improvement of waste reduction in the OR requires better waste management and segregation. There were also two guidelines regarding this subject. Indeed, there is high GHG emission during the waste destruction process, which may have a significant impact. Therefore, segregation of waste is crucial to improve many other climate-smart actions as it impacts waste reduction, recycling, reprocessing, or reuse.

In the OR, there are mainly two types of waste:

1. Regulated medical waste (RMW) that corresponds to health care-related waste with the potential to spread diseases through blood or other type of contamination if not handled properly. Contaminated items are defined as waste that would release blood or other potentially infectious materials in a liquid or semiliquid state if compressed. This waste cannot be recycled and are mostly incinerated.

2. Domestic waste (or nonhazardous waste or general waste) including all uncontaminated medical and nonmedical waste. These do not pose any particular biological, chemical, radioactive, or physical hazard.

Twenty years ago, the Association of periOperative Registered Nurses (AORN) elaborated recommendations to improve segregation of waste and to take advantage of recycling and reusing medical equipment [19]. These guidelines promoted, among the nurses' community, the awareness of recyclable waste in perioperative settings such as paper, polypropylene, polystyrene, high-density polyethylene, glass, and aluminium.

The Association of Perioperative Practice in the UK edited guidelines in 2013 with colour–labelled containers to segregate waste (Supplementary Figure 1) [20]. Although this specific classification is not commonly used worldwide, it is widely accepted that it is one of the first steps for better waste segregation. In the OR, there are usually two types of bags: domestic (black) and RMW (yellow). RMW bags are normally restricted to highly offensive sanitary waste, but the lack of awareness and education often leads to wrong segregation. Although the colour labelling to segregate waste proposed in the UK is applied in some countries, there is no official commonly accepted colour for each type of waste. The application of a homogeneous colour label would help improve the compliance of every health worker; in that regard, the World Health Organization recommend that yellow should be used for infectious waste, brown for chemical and pharmaceutical waste, and black for general waste [21].

Francis et al [22] studied the impact of the colour code for waste bag to improve segregation. They tried to determine whether any waste was labelled incorrectly as infectious or whether it contained potential recyclable material. After 30 d of using separate coloured bags, they found a 30% increase of domestic waste in the OR. Similarly, incorrect segregation was shown in a prospective study evaluating arthroplasty procedures, where 30% of total waste in the OR was mislabelled and should have been considered uncontaminated or cleaned and potentially recycled [23].

Indeed, identification of domestic waste is an easy action to improve segregation. In a study evaluating 51 surgical procedures, the use of domestic waste containers before patient entry in the OR reduced RMW by 13 800 kg/yr [24]. Another example of waste segregation showed that the classification of CO_2 absorbers as domestic waste could lead to a 2.8 tons/yr of waste reduction without any risk for the OR staff or the patients [25].

A large survey among 783 staff members and 352 gastroenterologists showed that 50% segregated some accessories as RMW instead of domestic waste, and that one-third discarded endoscopy accessories (RMW) and nasogastric tubes (domestic waste) differently despite the same degree of contamination [26]. Overall, 98% of the participants declared that education regarding waste segregation was not sufficient [26]. This lack of awareness and need for educational programmes were also strengthened in a large nationwide survey among American anaesthesiologists where 60% of the participants considered that there was a lack of information regarding segregation in the OR [27].

Education was not only lacking for health care workers, but also found to have an indirect impact, being highly effective to improve waste management. Three quantitative studies assessed the implementation of an educational programme for the OR staff. Martin et al [28] implemented an educational programme for waste segregation in the OR, and have shown a significant decrease in domestic waste and an increase in recyclable waste. The weight of recycled material and the number of waste bags increased, respectively, by 19% and 45% per OR per day. Another similar programme evaluated in 21 ORs permitted a 66% increase in domestic waste and an 82% reduction of RMW [29]. The misappropriation of domestic waste into RMW is an important source of GHG emission, and educational programmes using photos to provide a visual emphasis obtained a 50% waste reduction for both laryngoscope blades and endotracheal tubes [30].

Waste segregation is the backbone of any climate-smart action in the OR. Despite national and local rules for segregation, there is a lack of education to improve and accurately segregate waste. Therefore, similarly to radiation protection programmes that are already implemented for OR staff, a dedicated educational programme should be implemented systematically in every institution (or even better, at medical schools) to improve correct segregation

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and collective awareness of sustainable values. Examples of awareness strategies to improve segregation, reduce the use of RMW bags (yellow), and use the domestic bags appropriately are proposed in Figure 3 and Supplementary Figure 2.

3.3. *Improve waste reduction and recycling*

Waste recycling and reduction are actually two main points to be considered in a strategy aiming to implement sustainable actions in the OR. We identified in the literature 11 studies assessing these two subjects.

Wormer et al [31] elaborated a greening campaign structured on four points: (1) solid waste reduction, (2) OR recyclables and reusables, (3) energy and water reduction, and (4) charitable donations. Overall, thanks to points 1 and 2, their efforts led annually to a 75% reduction of RMW bags, 243 tons of CO_2 emission reduction with a "power down" programme, 2.7 million litres of water saved, and 6000 kg of diverted waste reduction.

To improve the waste management related to surgery, waste production must be considered all along the patient pathway (before, during, and after the surgery), as different waste is produced and several specific actions could be implemented at each step.

During the preparation of the surgery, an important volume and weight of paper and cardboard are produced and should be recycled. A prospective study found that 3.05 kg of waste per patient was produced in the theatre preparation room (67% were paper and cardboard) and 1.3 kg of waste per patient (50% were paper and cardboard) in the anaesthetic room; 24.7% of this waste could be recycled [32]. Similarly, Lui et al [33] showed that before otolaryngology—head and neck surgery (OHN), 90% of the waste generated was recyclable; the major contributors were polyethylene wrapping, high-density polyethylene bottles, paper, and blue sterile wrapping. Blue sterile wrapping (polypropylene plastic) especially used for the storage of surgical equipment could also be replaced with hard cases, leading to a reduction of 5 tons/yr of blue wrap consumption in their institution [34]. Another part of the preoperative waste management pointed by Fisher [20] was the need to include the storage and frequency of product collection in order to reduce quantities to operate on a just-in-time basis and limit the risk of expiry and nonuse of products.

During surgery, an important part of the waste produced could come from the devices used, especially when these are disposable. Indeed, in a recent study that proposed a simplified method to estimate a part of scope 3 (definition in Table 1), which comprised manufacturing of surgical device- and non–device-associated products, up to 86% of the GHG emission were attributed to disposable packaging and user manuals [35]. The study highlighted the urgent need for recycling programmes and other manufacturing/-packaging modifications that could reduce the quantity of waste produced. In their study, Thiel et al [36] determined the CF of sustainability interventions applied during laparoscopic hysterectomy; the largest CF saving came from decreased material consumption and selection of cleaner anaesthetic gas. When replacing desflurane with sevoflurane, GHG emission was decreased by 25%. Additionally,

Fig. 3 – Examples of awareness-raising campaigns for (A) improving segregation and (B) reducing the misuse of regulated medical waste bags. OR = operating room.

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minimisation of material use and selection of reusable surgical instruments permitted a 70% reduction of GHG emission per case [36].

It has also been shown that reduction and recycle of waste actions were applicable after surgery. A pilot study in neurosurgery, implementing a blue wrap recycling project (where the wraps were baled and sold to recyclers who pelletised and transformed it into plastic products) permitted a $5000 annual revenue and a $174 000 cost avoidance with 14.5 kg of blue wrap collected per day [37]. From this pilot study, the authors projected that 80% recycling of blue wrap at their institution would lead to a decrease of 25 tons of waste and saving of 158 000 kWh of electricity during the study period of only 8 wk.

Hence, improving surgical blue wrap management has great potential in that regard: first, by reducing its use by implementing hard cases for the conditioning of surgical devices; second, by improving segregation by considering it as domestic waste (black bags) in most of the cases; and finally, by proposing recycling programmes to external companies. Moreover, according to local and national policies, most of the pads and gowns used during surgeries could also be considered domestic waste instead of RMW, thereby improving the quantity as well as the quality of the waste produced. Indeed, although waste reduction is not always possible, the quality of waste produced is an important factor that could improve our recyclable actions. Lee and Mears [34] found that 73% of incinerator waste was produced in the OR without meeting federal guidelines (being visibly soiled, dripping, or covered with human fluids). They implemented disposal and waste reduction methods separating waste generated before the entry of the patient in the OR from waste generated during surgery, and had a 50% reduction of their annual waste output by recycling the optimal segregated waste.

Education for recycling is perceived as an unmet need by health care workers, although it seems to improve long-term behaviour in the OR [27]. These findings were supported by Azouz et al [38] who reported that 56% of the OR staff did not know which items were recyclable and by Petre et al [39] who showed that, among 400 responders, >60% estimated the lack of support from the hospital leadership and inadequate education as the main barriers to recycling in the OR. Interestingly, >50% of the anaesthesiologists reported that the greatest barriers to recycling waste in the OR were inadequate recycling facilities [40]. Therefore, education should lead to immediate practical actions that imply the allocation of necessary facilities for effective recycling.

Although these efforts for recycling do not decrease GHG emission drastically, these are a keystone for a complete programme of sustainability as these can be implemented easily and have a potential impact on notably reducing long-term expenditures of furniture.

Overall, to improve recycling and reduce waste production in the OR, it is important to create educational programmes and improve awareness. These actions should be carried out in line with the implementation of dedicated recycling facilities adapted to the patient pathway. Pre-, intra-, and postoperative steps require different recycling facilities and specific actions that are easy to target and implement, and must become a major concern to improve our sustainability behaviours in the OR.

3.4. *Improve reuse and reprocessing*

Reuse of material and equipment were evaluated in seven studies. Conrardy et al [41] conducted a comparison study between two OR departments to evaluate the effect of reusable surgical basins, gowns, and Mayo stand covers. The materials were adapted to the type of surgery using the classifications of the Association for the Advancement of Medical Information (AAMI) based on four different categories of barrier materials [42]. The implementation of reusable products led to a 59–70% reduction in surgical waste production. Moreover, another study evidenced a 10% decrease in GHG emission per case when reusable equipment was used during laparoscopic hysterectomy [36]. However, McGain et al [43] highlighted an increase of 10% CO_2 emission for reusable anaesthetic equipment compared with disposable equipment (respectively, 5575 and 5095 kg of CO_2). Also in anaesthesiology, a prospective study has shown that reusable central venous insertion catheter kits had less CO_2e emission (respectively, 1211 vs 407 g per kit) and water use (27.7 vs 2.4 l per kit) than the disposable ones [44]. In urology, the CF of disposable and reusable ureteroscopes was found to be similar (respectively, 4.43 and 4.47 kg) [45]. Another study performed a screening life-cycle assessment of disposable and reusable surgical scissors [46]. The authors showed that stainless-steel disposable scissors had the greatest impact when compared with stainless-steel reusable scissors or plastic disposable scissors (equivalent to 2% and 20% of the stainless-steel reusable scissors, respectively). Finally, in an OHN study where the authors used rigorous methods to assess the cradle-to-grave life cycle and life-cycle costing, reusable laryngoscopes produced much less emission and were significantly cheaper [47].

During the past decade, there was a strong increase in the consumption of disposable medical devices (DMDs), which are now being displaced by reusable ones. Therefore, a system change for medical devices, from a resource-intensive supply chain towards a more sustainable value creation chain by increasing the product life cycle through reprocessing, appears urgent.

Reprocessing of DMDs is feasible and effective, especially after running specific evaluations. Abreu et al [48] proposed a comprehensive programme model to evaluate the potential and safety of reprocessing DMDs based on three phases: (1) a device audit, (2) a laboratory evaluation, and (3) a clinical evaluation. Although they showed the efficiency of the programme, they underlined the need for on-going evaluations to ensure that the safety levels and cost savings established during the initial audit and evaluation phases continue. The AORN has also issued in 2001 guidelines for the reuse of single-use devices based on federal drug administration (Food and Drug Administration) guidance [49], but these are not applicable abroad and need to be updated regarding the new regulations. Another study found that devices such as single-use sphincterotomes

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could be reused [50]. Moreover, Roth et al [51] evaluated reprocessed laparoscopic single-use devices (monopolar scissor and ultracision harmonic scalpel), and found that either cleaning or disinfecting product could not be completely efficient on single-use device shape or surface. Therefore, the safety regarding infection rates of reprocessing/reuse of single-use devices is not yet proved and need further specific investigations.

Despite the great potential perspective of the implementation of DMD reprocessing, it remains illegal in many countries where regulations prohibit giving "second life" to DMDs. This is in contrast to other countries including Germany and the USA where reprocessing of single-use medical devices (SUMDs) is legal under certain constraints for hospitals and third party reprocessors. Indeed, in several countries, manufacturers decide whether their products are declared single- or multiple-use types without the need to justify to the authorities.

Overall, we found that the implementation of reprocessing of SUMDs as well as reducing their use has an important impact on waste production and consequently on the environment. Although SUMDs might have a lot of benefits, clinicians and stakeholders should consider the CF and should better assess their indication to regulate their use. Moreover, manufacturers and institutions should work hand to hand, in advance of any contract agreement, to propose dedicated reprocessing pathways to reduce the CF of waste produced.

3.5. *Sterilisation*

An important point in the choice between single-use and reusable devices is the concern about sterilisation. Both sterilisation and the waste this process produces must be taken into account when considering the use of reusable products in the OR. Indeed, the impact of sterilisation and its GHG emission are poorly assessed and deserve better attention from our community. In the last decades, hospitals modernised their sterilisation process with either ethylene oxide or radiation technologies, opening up the ability to reuse disposables [52], but data regarding their ecological impact remain weak. We identified one guideline and five studies evaluating the impact of sterilisation.

Recently, the Asia Pacific Society of Infection Control reported the environmental issue of sterilisation in the recommendations for disinfection and sterilisation of instruments [53]. The society recommended considering environmental safety and biodegradability when selecting a disinfectant for reprocessing medical equipment. However, the authors did not give more precision or a course of action that could be implemented in hospitals.

Although reuse seems to decrease medical waste, sterilisation process may counterbalance this advantage. Indeed, in a prospective study, Adler et al [54] compared the cost and impact of sterilisation of 255 laparoscopic reusable instruments (trocar, Veress cannula, and scissors). Sterilisation consumption during the study period included 373 m^3 of water, 5249 kWh of energy, 76.5 l of cleaning agents, and 4569 l of steam. Despite a lack of GHG emission assessment, the authors estimated that the use of disposable instruments would have resulted in 295.8 kg of household waste, 142 kg of cardboard, and 375.8 kg of plastic waste. They also performed an economic evaluation where the use of disposable instruments was 19 times more expensive than reusable ones.

In their study comparing reusable versus disposable catheter kits, McGain et al [44] found that for reusable kits, the main CO_2e emission and water use came from sterilisation and washing. Indeed, of 27.7 l of water used for reusable devices, 11.2 l (40.4%) were for washing and 15.7 l (56.7%) for sterilisation. Additionally, washing and sterilisation emitted, respectively, 256 (21.1%) and 830 g (68.5%) of CO_2 for reusable devices [44]. These results are also described by Leiden et al [55], who showed the high environmental impact of steam sterilisation for reusable surgery instrument set for spinal fusion. In their study, about 90% of the GHG emission was caused by cleaning and sterilisation. The authors also underlined that the design of future reusable equipment should permit low-effort cleaning and sterilisation.

Therefore, efforts to reduce the environmental footprint of reusable items should be directed towards decreasing water and energy consumed in cleaning and sterilisation. For reusable devices in anaesthesiology, washer and H_2O_2 steriliser electricity were responsible for, respectively, 86% and 7% of GHG emission [43]. Nevertheless, they acknowledge the lack of external applicability of their results as CO_2 emission from reusable equipment would have been lower if their hospitals were located in Europe or in the USA. Finally, a study comparing the CF between reusable and disposable ureteroscopes has shown that the main CO_2e for reusable ureteroscopes were generated by sterilisation (3.95 kg of CO_2 per case accounting for 88.4% of total CO_2 emission), whereas it was mainly caused by the manufacturing of disposable equipment (3.84 kg of CO_2 per case accounting for 86.5% of total CO_2 emission) [45].

In conclusion, although sterilisation was not precisely in the scope of the OR, we found many articles that addressed its potential impact on GHG emission. Whereas none of the studies proposed clear strategies to reduce its impact, they all found that sterilisation for reusable equipment deserves more research and development in the near future. A design permitting low-effort cleaning and sterilisation for reusable equipment could be a promising lead to reduce sterilisation impact. Moreover, reducing the number of devices that need sterilisation could also be an efficient way to reduce environmental impact and lower economic costs.

It also needs to be underlined that the lack of studies regarding the processing of the waste created during sterilisation (ie, liquids, gases, etc.) may have a strong impact and need to be considered for the CF estimation of reusable devices.

3.6. *Anaesthetic gas management*

Three studies underlined the impact of anaesthetic gases [9,36,56] on GHG emission. A prospective study involving three different centres from the USA and Europe found that anaesthetic gases and energy consumption were the largest sources of GHG emission [9] in the OR. Interestingly, emis-

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sion due to anaesthetic gases was around 2000 tons CO_2e per hospital per year in the USA, whereas this was ten times lower in the European department. This difference was explained by the absence of desflurane utilisation in the UK (due to its cost); despite its fast induction and emergence, desflurane has very high GHG emission and has been pointed out as the biggest contributor to anaesthetic gas emission [57]; for instance, GHG emission of this gas is five-fold higher than that of isoflurane and 20-fold higher than that of sevoflurane. Another study found that the removal of desflurane would reduce GHG emission by 25% during laparoscopic surgery [36]. Tempia et al [56] evaluated an anaesthetic conservative device that vaporises sevoflurane under different fresh gas flow conditions to reduce volatile anaesthetic consumption and environmental pollution, but has not been implemented widely.

In conclusion, there is also a need to improve awareness of anaesthesia products and their impact of the climate, which might improve the wide spread of climate-smart actions [58]. This concern regarding anaesthetic gases should also make health care workers more careful and propose more alternative anaesthetic options such as local, regional, or total intravenous anaesthesia after consultation with anaesthesiologists.

3.7. *Energy efficiency in the OR*

Fossil fuel combustion is the dominant source of health care climate emission. The use of coal, oil, and gas to power hospitals, health care-related travel, and manufacture and transport of health care products comprises 84% of all health care-related climate emission across facility operations, supply chain, and broader economy. This is especially true for the operating theatre. Indeed, in the study by MacNeill et al [9], heating, ventilation, and air conditioning (HVAC) thermal energy systems comprised 90–99% of overall energy use. This is near twice the consumption of other inpatient health care facilities [59]. The authors underlined that occupancy-based ventilation strategies reduced unnecessary airflow to unused space and had the potential for considerable energy saving. They calculated that by reducing airflow rates overnight and on weekends, keeping only three of 22 theatres online for emergencies, there was a 50% reduction in HVAC energy consumption.

In this context, Lin et al [60] applied, in a pilot study, a radiofrequency identification system that automatically controls high-efficiency particulate air (HEPA) ventilation. The HEPA ventilation turned on and adjusted itself according to the number of persons in the OR. The authors indicated that the system was working correctly in 98–99% of the cases and could generate 50% energy saving [60].

The high need to decrease energy consumption in the OR is also considered in the recent high-impact actions proposed by Health Care Without Harms in collaboration with ARUP—an independent firm working across every aspect of today's built environment—as a global road map for health care decarbonisation [61], including the following: (1) power the OR with 100% clean, renewable electricity; (2) invest in zero-emission infrastructure; and (3) transition to zero emission, and sustainable travel and transport by encouraging active travel and public transport for patients and staff wherever feasible.

In conclusion, energy consumption is the highest source of GHGs in the OR, but it is also the one where surgeons and the surgical staff have less impact. Therefore, surgeons need to push stakeholders and institution directors to set up actions in this regard, such as encouraging the construction of a sustainable OR.

3.8. *Discussion*

Our study is not without limitations that should be acknowledged. First, the studies included were heterogeneous and did not allow reporting of accurate evaluation regarding CO_2 emission in the OR. Indeed, we strengthened the lack of studies and data regarding the assessment and improvement of environmental and sustainability actions. We have identified actions that have a CF leverage, but the environmental impact remains unknown. A more accurate assessment of surgical supply chain emission, with CF evaluation adapted to local regulations and economic evaluation, would probably improve the overall evaluation [62].

One of the main reasons for discrepancies between CF evaluation remains in the heterogeneous methods of calculation used and the broad spectrum of scopes considered in the analysis. For the CO_2 emission evaluation, emission factors (a coefficient that allows converting activity data in GHG emission, taking into account extraction/production and transport of every raw material) should be sourced from national public databases that vary among countries [63]. Additionally, the cradle-to-grave assessment that would include the three scopes of GHG emission evaluation should be the standard methodology. Nevertheless, it remains difficult to apply this method for each specific action in the OR, and further efforts should be made to improve it. Overall, there are still many debates regarding the best way to assess the CF as well as the way to improve our sustainability practices.

Moreover, to enhance the implementation of these climate-smart actions, it would be essential that clinicians and hospitals can monitor these shifting resources and policies outside of the health care sector to see the influence on the downstream impact of these programmes.

Whilst we may care about the protection of the environment in our personal lives outside the hospital, our work sphere seems to be a different realm. Unfortunately, it is now recognised that we have only a small window in which we all must take actions [64–67]. Therefore, this systematic review is an advocacy to compel surgical community to promote and assess existing climate-smart actions to improve the development of sustainability (Fig. 2). The future of surgical practice should absolutely account for the CF and climate impact of the care provided. It is actually time for changing the rules for the next generations of surgeons.

4. Conclusions

Climate-smart actions in the OR are urgently needed and deserve more awareness and implementation. Although some actions are mainly the role of stakeholders, many of them are within reach and should be applied immediately by the health care providers working in the OR. More educational programmes should be implemented for health care workers as well as those in training. Reducing waste production, improving segregation, and recycling protocols are the easiest actions to implement, and these would allow a concrete revolution of thinking about surgical impact on the environment for now and for the next generations. This review underlined that the operating theatre field is lagging behind other sectors, and needs to harmonise the actions and pool its strengths to improve. Further multidisciplinary consensus is needed to provide quality endpoints to use in this setting, and to improve the completeness and transparency of reporting of studies that assess climate-smart actions. Future studies focusing on the climate impact of our actions are needed and should be awarded in the surgical community.

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Study concept and design: Pradere, Pinar, Mallet.
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Analysis and interpretation of data: Pradere, Pinar, Misrai, Mallet.
Drafting of the manuscript: Pradere, Pinar, Misrai, de La Taille.
Critical revision of the manuscript for important intellectual content: Mallet, Game, Fournier, Mejean, Bladou, Prunet, Beurrier, Bardet, Lechevallier, Meria, Matillon, Polguer, Abid, De Graeve.
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