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GENERAL ORTHOPAEDICS

# Environmental sustainability in orthopaedic surgery

## A SCOPING REVIEW

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### Aims
In the UK, the NHS generates an estimated 25 megatonnes of carbon dioxide equivalents (4% to 5% of the nation's total carbon emissions) and produces over 500,000 tonnes of waste annually. There is limited evidence demonstrating the principles of sustainability and its benefits within orthopaedic surgery. The primary aim of this study was to analyze the environmental impact of orthopaedic surgery and the environmentally sustainable initiatives undertaken to address this. The secondary aim of this study was to describe the barriers to making sustainable changes within orthopaedic surgery.

### Methods
A literature search was performed according to Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines through EMBASE, Medline, and PubMed libraries using two domains of terms: "orthopaedic surgery" and "environmental sustainability".

### Results
A total of 13 studies were included in the final analysis. All papers studied the environmental impact of orthopaedic surgery in one of three areas: waste management, resource consumption, and carbon emissions. Waste segregation was a prevalent issue and described by nine studies, with up to 74.4% of hazardous waste being generated. Of this, six studies reported recycling waste and up to 43.9% of waste per procedure was recyclable. Large joint arthroplasties generated the highest amount of recyclable waste per procedure. Three studies investigated carbon emissions from intraoperative consumables, sterilization methods, and through the use of telemedicine. One study investigated water wastage and demonstrated that simple changes to practice can reduce water consumption by up to 63%. The two most common barriers to implementing environmentally sustainable changes identified across the studies was a lack of appropriate infrastructure and lack of education and training.

### Conclusion
Environmental sustainability in orthopaedic surgery is a growing area with a wide potential for meaningful change. Further research to cumulatively study the carbon footprint of orthopaedic surgery and the wider impact of environmentally sustainable changes is necessary.

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**Keywords:** Orthopaedic surgery, Environmental sustainability, Environmental impact, Environmentally sustainable changes, Carbon footprint, Waste management, Resource consumption, Carbon emission

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## Introduction
Climate change poses one of the largest health emergencies to humankind today,[1] which impacts health in the form of global warming, collapse of the Gulf Stream, extreme weather changes, environmental disasters, altered infectious disease patterns, pollution, loss of biodiversity, and scarcity of natural resources.[2-4] The World Health Organization (WHO) has predicted an excess in

mortality of over 250,000 fatalities per year as a consequence of climate change,[3,5] and over eight million deaths as a result of air pollution.[6]

The healthcare sector represents one of the largest contributors to the world's carbon footprint, second only to the food production industry.[7,8] Carbon dioxide ($CO_2$) and other greenhouse gases (GHG), produced by healthcare activities and collectively represented as carbon dioxide equivalents ($CO_2$e), trap heat within the atmosphere and, in excessive concentrations, negatively contribute to climate change.[9,10]

In the UK, the NHS generates approximately 4% to 5% of the nation's total GHG emissions,[1] an estimated 25 megatonnes of $CO_2$e annually.[11] The NHS also produces over 500,000 tonnes of waste annually, accounting for a quarter of all public sector waste.[1,9,12] Operating rooms (ORs) generate about 20% to 33% of a hospital's total waste,[9,13-16] where one surgery can generate more waste than a family of four can produce in a week.[14,17] This waste is segregated into waste streams for disposal either as landfill or incinerated using high-energy processes,[18] producing between 21 and 1,074 kg $CO_2$e per tonne.[19] Up to 90% of hazardous OR waste is thought to be inappropriately segregated and subsequently incinerated,[20,21] which has negative implications for the environment as it releases pollutants causing soil and water acidification, destruction of aquatic life, and mercury contamination of water sources.[15,22] Additionally, incineration costs ten to 20 times more for hazardous than non-hazardous waste.[20,23]

ORs are resource-intensive and are thought to use approximately three to six times more energy than other areas of the hospital,[9] with over 90% of OR energy used for maintaining heating, ventilation, and air-conditioning (HVAC) systems and operating powered equipment.[12] In the UK, a high-volume centre of 24 ORs generated over four million kg $CO_2$e annually in energy consumption for the maintenance of their OR HVAC systems.[12] To put this into perspective, the energy used to operate one OR could be used to power over 2,000 homes in the UK.[24]

In response to the dangers of climate change, the Paris Agreement, adopted by over 190 countries, was released by the Intergovernmental Panel on Climate Change and is committed to limiting the increase of global warming to 1.5°C.[1,25-27] According to the WHO, NHS England is the only healthcare system to date that has a published national strategy: the 'Greener NHS programme', addressing the issue of climate change in relation to healthcare and aims to achieve a net zero NHS by 2045.[28,29] The Royal College of Surgeons of England has also issued a modified triple bottom line framework (economic, environmental, and social sustainability)[14] aiming to improve sustainability within surgery.[30]

The principles of sustainability use a "5R" strategy – reduce, reuse, recycle, rethink, and research.[14,22] Many surgical fields are now striving to implement 'green' and sustainable practices. Efforts have been conducted to analyze these principles in practice and have demonstrated positive outcomes. Improved waste segregation in ORs has reduced inappropriate disposal and increased the amount of waste recycled.[7] Life-cycle assessments (LCAs), methods used to analyze the 'cradle-to-grave' impact of an item or procedure, are used to facilitate environmentally sustainable decision-making and procurement.[9,31] The optimization of surgical trays has shown a reduction in carbon footprint and overage of certain procedures, with trends moving towards reprocessing single-use or opting for reusable devices.[32] Efforts to minimize energy and water consumption in ORs have also demonstrated a reduction in carbon emissions and resource wastage.[9,12,20]

However, only a handful of studies demonstrate outcomes exclusively within orthopaedic surgery. Therefore, the aim of this study is to systematically review the existing literature discussing the environmental impact of orthopaedic surgery and describing current sustainable practices in orthopaedic surgery.

## Methods

A scoping review was conducted in accordance with the Preferred Reporting Items for Systematic Review (PRISMA) Extension for Scoping Reviews protocol,[33] and registered with the International Prospective Register of Systematic Reviews (PROSPERO). This study was guided by the five-stage scoping review process described by Arksey and O'Malley,[34] including adaptations from Levac et al[35] and the Joanna Briggs Institute.[36] The study primarily aimed to evaluate existing literature discussing the environmental impact and sustainable practices within orthopaedic surgery. The secondary aim was to describe the barriers to implementing sustainable changes within orthopaedic surgery.

A search was performed on 17 September 2021 using the Medline, EMBASE, and PubMed databases (Supplementary Tables i and ii). Additional grey literature search was also performed on OpenGrey. Irrelevant or duplicate articles were discarded. The titles and abstracts from the initial search were independently screened by two reviewers (KMP, IA) against a set of eligibility criteria (Figure 1). The full texts of the remaining articles were obtained and further screened (KMP, IA). Reference lists of the included articles were screened to identify any further relevant articles. Conflicts were resolved through a discussion in the presence of senior authors (VA, DK).

Data from the included articles were extracted and input into a spreadsheet using a standardized proforma, and included study characteristics, environmental issue addressed, barriers, and recommendations. The studies were grouped according to the environmental issues addressed. The level of evidence for each article was

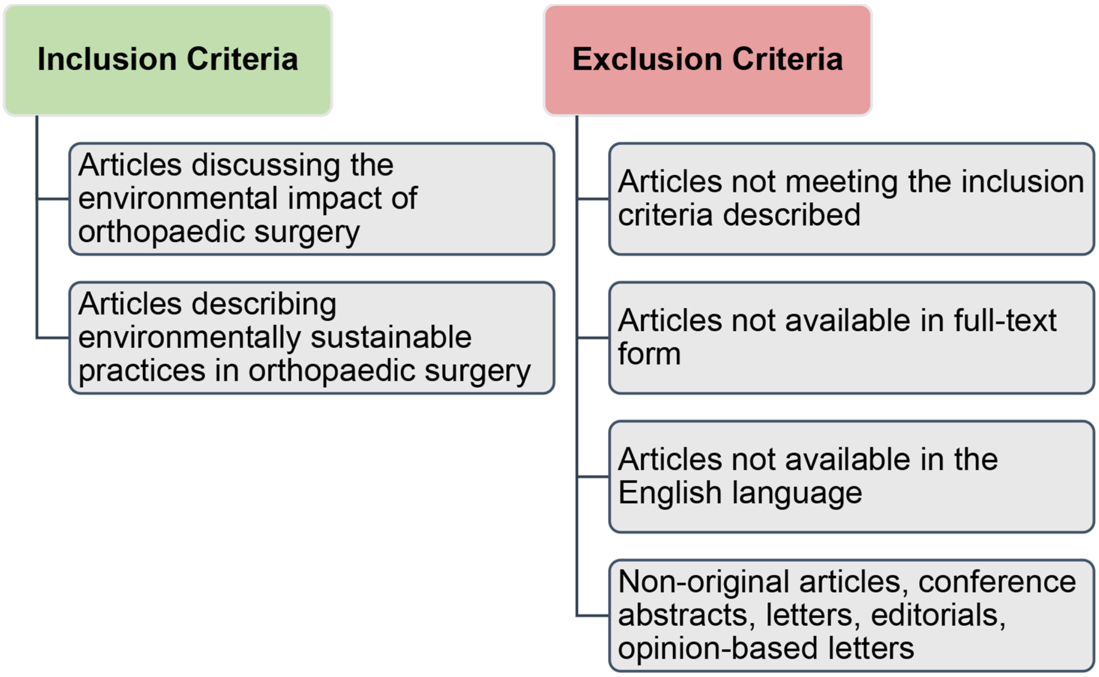


**Fig. 1**

Inclusion and exclusion criteria used for the study selection.

assessed using the Oxford Centre for Evidence-Based Medicine (OCEBM) Levels of Evidence tool,[37] and risk of bias was assessed using a modified Methodological Index for Non-Randomised Studies (MINORS) tool.[38]

As this study is based upon previously published studies, no patient data were recorded, no ethical concerns were identified, and no ethical approval was required for this process.

## Results

The initial search yielded 3,138 results. Of these, 473 duplicate records were removed, 2,611 were excluded following the title and abstract screening, and 41 articles were further excluded following the full-text review. A total of 13 articles were included in the final analysis (Figure 2). No further articles were identified from a search of the reference lists of included articles or the grey literature search.

Three main environmental issues were identified. Nine studies focused on waste management,[18,39–47] three on carbon emissions,[48–50] and one on water usage[51] (Table I). The quality assessment of the studies is detailed in Figure 3.

**Waste management.** Waste management was described by nine articles (Table II),[18,39–46] which investigated waste segregation in practice. The number of waste streams across these studies ranged between two and eight. Only two studies reported identical waste streams;[18,42] however, the proportion of waste for each stream was different.

Across the studies, a total of 1,824.7 kg of waste was generated. Normal, domestic, or uncontaminated waste ranged from 6.4 kg to 188.2 kg (13.5% to 46.8%). Conversely, biohazardous or contaminated waste ranged from 12.8 kg to 213.8 kg (19.2% to 74.4%). Thiel et al[46] reported a total of 438 kg of waste generated across 178 hand surgery procedures, but did not specify the types of waste streams used.

Eight studies were conducted perioperatively across a total of 317 procedures of varying orthopaedic subspecialties (Table III).[18,39,40,42–46] Four of these included waste generated from the point of opening surgical kits to the disposal of all equipment and items used for the procedure.[18,42,44,45] Two studies calculated waste generated from within the sterile field.[40,43] Hennessy et al[43] observed waste generated only from implants used intraoperatively.

The results showed that 0.2 kg to 15.1 kg of waste was generated per procedure. Four studies reported that total hip arthroplasties (THAs) and total knee arthroplasties (TKAs) generated the highest amount of waste by mass compared to other types of procedures, where THA produced 12.6 kg per case (12.1 to 13.6), and TKA produced 13.1 kg per case (11.6 to 15.1).[18,39,40,45]

Theil et al[46] was the only study investigating the benefits of using customized leaner surgical packs in hand surgery, in combination with the Wide Awake Local Anaesthesia No Tourniquet (WALANT) method.[32] The authors found that the WALANT method generated significantly less waste compared to using sedation and local anaesthetic (12%; $p < 0.005$). This reduction was compounded by using the leaner packs (13%; $p < 0.005$).

Recycled waste was reported in six studies (Table IV),[18,39,40,42–44] which totalled 196.292 kg (0.042

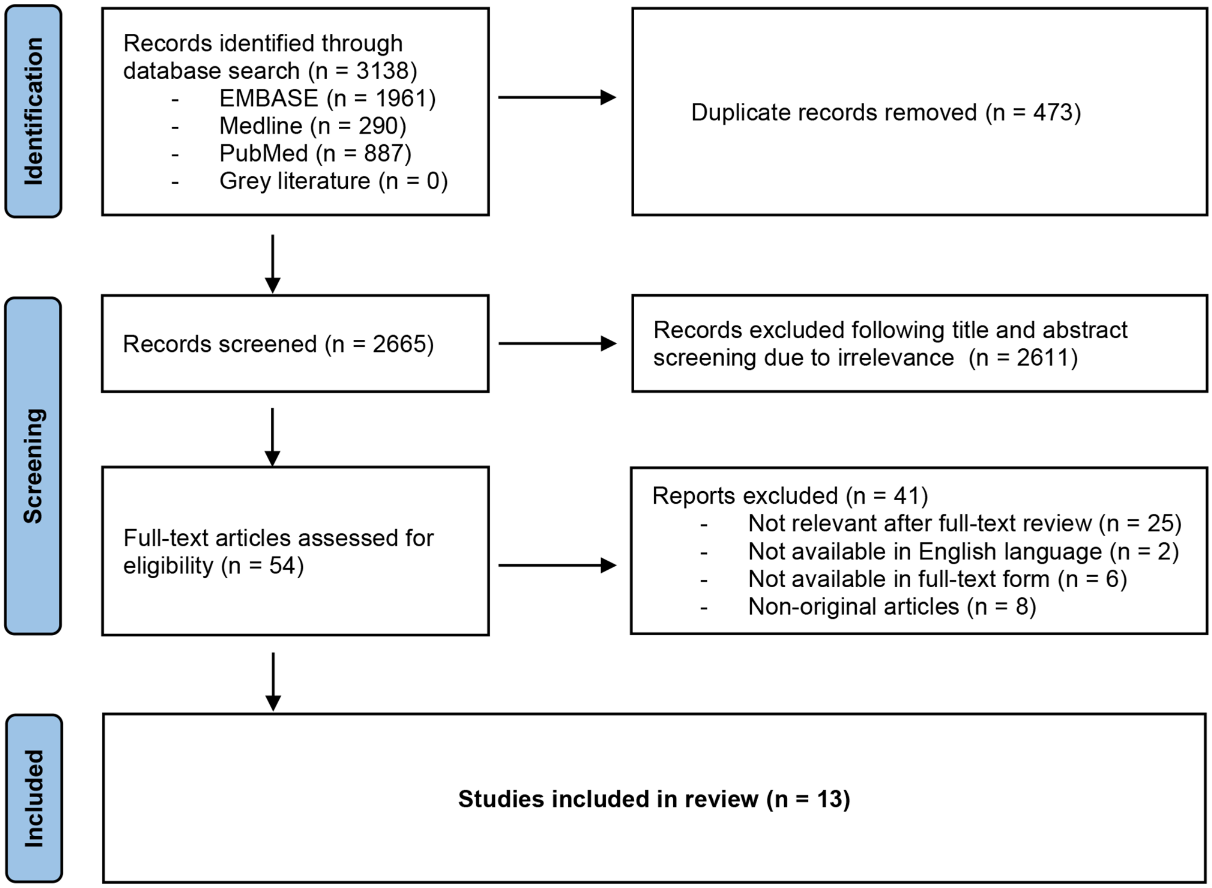


**Fig. 2**

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram showing study selection.

to 93.400kg; 14.3% to 43.9%). Kooner et al[44] reported that arthroplasty and paediatric orthopaedic procedures generated a significantly higher proportion of recyclable waste compared to other subspecialties included in the study (33.5% and 42.6%, respectively; $p < 0.05$). Hennessy et al[43] reported only 0.042 kg of recyclable waste (20% of total waste from study) was generated from one ankle open reduction internal fixation (ORIF).

Three studies segregated sterile polypropylene ‘blue’ wraps, which are made of plastic and used to maintain the sterility of surgical equipment, as a standalone waste stream.[18,42,45] These studies reported generating between 5.2 kg and 11.7 kg of sterile wrap (6.2% to 24.6%). However, this was recycled in only two studies.[18,42]

Overage refers to any items prepared or opened during but remained unused by the end of a procedure. Two studies reported various amounts of overage (Table V),[18,42] which commonly included green sterile towels and sterile surgical gloves. Overage from both these studies were disposed of as landfill waste.

**Carbon emissions.** Three studies investigated the carbon emissions generated by orthopaedic activities (Table VI).[48–50] Baxter et al[48] investigated the $CO_2$ emissions generated by ten frequently used items across three different hand surgery procedures performed by 32 different surgeons. This study reported a range of 7.8 kg to 28.8 kg of $CO_2$ emissions generated through the use of these items. Surgeons with leaner practices generated 10.9 kg fewer $CO_2$ emissions than other surgeons.

Leiden et al[50] compared the $CO_2$e emissions generated from the disposable and reusable instrument sets required to perform a single-level lumbar fusion surgery. This study reported that steam sterilization required for the reusable set generated higher levels of $CO_2$e emissions than Cobalt-60 ($^{60}$Co) gamma radiation required for the disposable set.

Curtis et al[49] compared the $CO_2$e emissions between face-to-face (F2F) and non-face-to-face (NF2F) outpatient orthopaedic appointments, which demonstrated that NF2F telephone consultations generated 5,846 kg $CO_2$e (58%) fewer $CO_2$e emissions compared to F2F appointments. Additionally, in terms of $CO_2$e emissions generated from travel to and from appointments, NF2F consultations reduced emissions by 563.9 kg $CO_2$e (66%), or 3.1 kg $CO_2$e per patient.

**Water usage.** Only one study investigated water usage in the orthopaedic OR (Table VII),[51] comparing a

**Table I.** Characteristics of included studies.

| Study (year) | Country | Type | Issue | Setting | Number | Period |
|---|---|---|---|---|---|---|
| Alam et al (2008) | Bangladesh | Prospective cross-sectional | Waste management | Inpatient ward | 1 ward (88 beds) | 6 mths |
| Baxter et al (2021) | USA | Retrospective case series | Carbon emission | Perioperative | 96 cases performed by 32 surgeons (32 CTR; 32 ORIF; 32 PFTR) | 1 mth |
| Curtis et al (2021) | UK | Retrospective cohort | Carbon emission | Outpatient clinic | 180 cases (76 F2F; 104 NF2F) | 1 mth |
| De Sa et al (2016) | Canada | Prospective case series | Waste management | Perioperative | 5 FAI hip arthroscopy | 1 mth |
| Hennessy et al (2021) | Ireland | Prospective case series | Waste management | Perioperative | 5 cases (1 ankle ORIF; 1 humerus ORIF; 1 clavicle ORIF; 1 hip hemiarthroplasty; 1 kyphoplasty) | 1 yr |
| Kooner et al (2019) | Canada | Prospective case series | Waste management | Perioperative | 55 cases (14 arthroplasty; 10 sports; 10 trauma; 12 upper limb; 4 foot & ankle; 5 paediatric) | 1 mth |
| Lee et al (2012) | USA | Prospective case series | Waste management | Perioperative | 20 cases (10 THA; 10 TKA) | 2 mths |
| Leiden et al (2020) | Germany | Prospective case series | Carbon emission | Perioperative | 2 single-level lumbar fusion | N/R |
| Potgeiter et al (2020) | South Africa | Prospective non-randomized controlled | Water usage | Preoperative | 64 scrubs (32 surgeons) | 12 hrs |
| Shinn et al (2017) | South Korea | Prospective case series | Waste management | Perioperative | 5 cases (4 TKA; 1 THA) | 1 mth |
| Southorn et al (2013) | UK | Prospective case series | Waste management | Perioperative | 44 cases (18 THA; 14 TKA; 12 FJI) | 2 wks |
| Stall et al (2011) | Canada | Prospective case series | Waste management | Perioperative | 5 TKA | 1 month |
| Thiel et al (2019) | USA | Prospective cohort | Waste management | Perioperative | 178 cases (80 CTR; 39 TFR; 32 cyst/ mass excision; 27 other) | 14 months |

CTR, carpal tunnel release; FAI, femoroacetabular impingement; F2F, face-to-face; FJI, facet joint injection; NF2F, non-face-to-face; N/R, not recorded; ORIF, open reduction and internal fixation; PFTR, primary flexor tendon release; TFR, trigger finger release; THA, total hip arthroplasty; TKA, total knee arthroplasty.

| Articles | Study Aim | Population | Functional Unit/ Intervention | Measurement of Outcomes | Results | Missing Data | Study Assumptions | Comparability | Level of Evidence |
|---|---|---|---|---|---|---|---|---|---|
| Alam 2008 | 2 | 1 | 1 | 2 | 1 | 1 | 0 | 2 | IV |
| Baxter 2021 | 2 | 1 | 2 | 1 | 1 | 0 | 1 | - | IV |
| Curtis 2021 | 1 | 2 | 2 | 1 | 1 | 1 | 0 | 2 | III |
| De Sa 2016 | 2 | 1 | 2 | 2 | 2 | 2 | 0 | - | IV |
| Hennessy 2021 | 1 | 0 | 2 | 2 | 1 | 1 | 0 | - | IV |
| Kooner 2019 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | - | IV |
| Lee 2012 | 0 | 2 | 1 | 1 | 1 | 2 | 2 | - | IV |
| Leiden 2020 | 2 | 1 | 2 | 2 | 1 | 2 | 0 | - | III |
| Potgeiter 2020 | 2 | 1 | 2 | 1 | 2 | 2 | 0 | 2 | IV |
| Shinn 2017 | 1 | 0 | 1 | 2 | 1 | 1 | 0 | - | IV |
| Southorn 2013 | 0 | 1 | 2 | 2 | 1 | 1 | 1 | - | IV |
| Stall 2011 | 2 | 1 | 2 | 2 | 2 | 2 | 0 | - | IV |
| Thiel 2017 | 2 | 2 | 1 | 2 | 2 | 2 | 0 | 2 | III |

**Fig. 3**

Quality assessment and level of evidence of studies.

standard scrub using water and soap to three different hand washing methods: alcohol scrub (AS), scrub nurse-assisted (SN), and self-wash (SW). SN and SW interventions involved switching water taps off when not in use during the process of scrubbing and used water and soap.

**Table II.** Waste segregation streams and amount of waste generated.

| Study (year) | Subspecialty | Setting | Functional unit | Cases, n | Total waste, kg | Waste stream | Total per stream, kg (%) | Waste per case, kg |
|---|---|---|---|---|---|---|---|---|
| Alam et al (2008) | Not specific | Inpatient ward | Waste generated on ward | 1 ward | 154 | Glass | 7.48 (4.86) | 1.75†<br>1.12‡ |
| | | | | | | Needle | 0.13 (0.08) | |
| | | | | | | Textile | 37.4 (24.3) | |
| | | | | | | Rubber | 4.43 (2.88) | |
| | | | | | | Plastic | 20.6 (13.38) | |
| | | | | | | Paper | 9.91 (6.44) | |
| | | | | | | Pack | 10.7 (6.95) | |
| | | | | | | Vegetable | 63.34 (41.1) | |
| De Sa et al (2016) | Hip arthroscopy | Perioperative | Opening of surgical kits to patient leaves theatre, all equipment disposed | 5 | 47.4§ | Normal/landfill | 6.4 (13.5) | 9.4 |
| | | | | | | Recyclable | 6.4 (13.5) | |
| | | | | | | Biohazard | 21.7 (45.7) | |
| | | | | | | Sterile polypropylene wrap | 11.7 (24.6) | |
| | | | | | | Sharps | 1.2 (2.6) | |
| | | | | | | Linens (excluded) | N/R | |
| Hennessy et al (2021) | Not specific | Perioperative | Waste generated only from implants | 5 | 4.791 | Cardboard | 2.748 (57.4) | N/R |
| | | | | | | Plastic | 2.023 (42.2) | |
| Kooner et al (2019) | Arthroplasty, upper limb, sports, trauma, paediatrics, foot and ankle | Perioperative | Opening of surgical kits to after theatre cleaned | 55 | 341 | Recyclable | 93.4 (27.4) | 6.2 |
| | | | | | | Non-recyclable | 239.1 (70.1) | |
| | | | | | | Biological | 8.5 (2.5) | |
| Lee et al (2012) | Arthroplasty | Perioperative | Waste generated within and leaving sterile field | 20 | 286.6 | Contaminated | 200.5 (69.9) | 14.3 |
| | | | | | | Uncontaminated | 86.2 (30.1) | |
| Shinn et al (2017) | Arthroplasty | Perioperative | Opening of surgical kits to all equipment and protective attire disposed | 5 | 84.4 | Regulated medical waste | 62.8 (74.4) | 16.9 |
| | | | | | | Non-regulated medical waste | 16.4 (19.4) | |
| | | | | | | Sterile polypropylene wrap | 5.2 (6.2) | |
| Southorn et al (2013) | Arthroplasty, spine | Perioperative | Waste generated throughout perioperative period, includes anaesthetic area | 44 | 401.8 | Domestic | 188.2 (46.8) | 9.1 |
| | | | | | | Clinical | 213.8 (53.2) | |
| Stall et al (2011) | Arthroplasty | Perioperative | Opening of surgical kits to all equipment and protective attire disposed | 5 | 66.7§ | Normal solid waste | 43.1 (64.5) | 13.3 |
| | | | | | | Recyclable clear plastics | 1.5 (2.2) | |
| | | | | | | Biohazard | 12.8 (19.2) | |
| | | | | | | Sterile polypropylene wrap | 8.1 (12.1) | |
| | | | | | | Sharps | 1.4 (2) | |
| | | | | | | Linen (excluded) | N/R | |
| Thiel et al (2019) | Hand | Perioperative | Waste generated from operation | 178 | 438 | Not recorded | N/R | 2.5 |

*88 beds, 137 patients per day.
†Per bed per day.
‡Per patient per day.
§Excluding linen.
N/R, not recorded.

The study concluded that the use of alcohol-only scrub used less water compared to all other methods (standard = 85.5% ($p < 0.001$); SN = 64% ($p = 0.033$); SW = 58% ($p > 0.05$)). Furthermore, alcohol-only scrub required significantly less time for scrubbing (standard = 80% ($p < 0.001$); SN = 73% ($p = 0.002$); SW = 80% ($p < 0.001$)).

**Barriers to sustainable practices.** All 13 studies commented on barriers to making sustainable changes within orthopaedic surgery (Table VIII).[18,39–46,48–51] The barrier most described by eight of the studies was a lack of appropriate infrastructure to support sustainable changes. Next was a lack of knowledge or training, as described by five studies.

**Table III.** Waste generated per orthopaedic procedure recorded.

| Article (year) | Cases, n | Total waste generated, kg | Type of procedure (n) | Mean waste per procedure, kg |
|---|---|---|---|---|
| De Sa et al (2016) | 5 | 47.4 | FAI arthroscopy (5) | 9.5 |
| Hennessy et al (2021 | 5 | 4.791 | Ankle ORIF (1) | 0.2 |
| | | | Humerus ORIF (1) | 0.2 |
| | | | Clavicle ORIF (1) | 0.5 |
| | | | Hip hemiarthroplasty (1) | 0.8 |
| | | | Kyphoplasty (1) | 3.1 |
| Kooner et al (2019) | 55 | 341 | Arthroplasty (14) | 8.8 |
| | | | Upper limb (12) | 4.6 |
| | | | Sports (10) | 5.0 |
| | | | Trauma (10) | 5.6 |
| | | | Paediatrics (5) | 5.6 |
| | | | Foot & ankle (4) | 4.9 |
| Lee et al (2012) | 20 | 286.6 | THA (10) | 13.6 |
| | | | TKA (10) | 15.1 |
| Shinn et al (2017) | 5 | 84.4 | THA (1) | N/R |
| | | | TKA (4) | N/R |
| Southorn et al (2013) | 44 | 401.8 | THA (18) | 12.1 |
| | | | TKA (14) | 11.6 |
| | | | FJI (12) | 1.8 |
| Stall et al (2011) | 5 | 66.7 | TKA (5) | 13.3 |
| Thiel et al (2019) | 178 | 438 | CTR (80) | 2.4 |
| | | | TFR (39) | |
| | | | Cyst/mass excision (32) | |
| | | | Other (27) | 2.8 |

CTR, carpal tunnel release; FAI, femoroacetabular impingement; FJI, facet joint injection; N/R, not recorded; ORIF, open reduction and internal fixation; TFR, trigger finger release; THA, total hip arthroplasty; TKA, total knee arthroplasty.

**Table IV.** Components of recyclable waste streams and amount of recyclable waste generated.

| Article (year) | Procedures, n | Components of recycling stream | Total mass recycled, kg (%)* | Mean mass recycled per case, kg (%)† | |
|---|---|---|---|---|---|
| De Sa et al (2016) | 5 | Recyclable clear plastic<br>Sterile polypropylene wrap | 18.1 (38.1) | 3.620 (38.1) | |
| Hennessy et al (2021) | 1 | Recyclable hard plastic | 0.042 (20) | 0.042 (20.0) | |
| Kooner et al (2019) | 55 | Plastics<br>Cardboard<br>Wrapping | 93.4 (27) | Arthroplasty | 2.956 (33.5) |
| | | | | Upper limb | 1.149 (23.2) |
| | | | | Sports | 1.008 (18.5) |
| | | | | Trauma | 2.342 (23.5) |
| | | | | Paediatrics | 2.158 (42.6) |
| | | | | Foot & ankle | 0.985 (20.7) |
| Lee et al (2012) | 20 | Paper<br>Plastic packaging material | 63.95‡ (22.3) | THA | 3.08 (22.8) |
| | | | | TKA | 3.31 (22.0) |
| Southorn et al (2013) | 44 | Dry paper and card<br>Recyclable plastic | 11.2§ (43.9) | N/R | |
| Stall et al (2011) | 5 | Recyclable plastic<br>Sterile polypropylene wrap | 9.6 (14.3) | 1.92 (14.4) | |

*As percentage of total waste.
†Percentage of waster per case.
‡Only from uncontaminated waste.
§Potentially recyclable.
N/R, not recorded; THA, total hip arthroplasty; TKA, total knee arthroplasty.

Other barriers described across the studies included lack of understanding of the benefits of sustainable practices (4/13), unclear guidelines or policies (4/13), resistance to change (4/13), lack of understanding of the environmental impact of current non-sustainable practices (3/13), and lack of incentive (2/13).

**Table V.** Overage.

| Article (year) | Procedures, n | Total overage (mean per case) | Common items used intraoperatively (n per case) | Destination of overage |
|---|---|---|---|---|
| De Sa et al (2016) | 5 | 75 green sterile towels (15)<br>50 sterile surgical gloves (10)<br>5 small unsterile towels (1) | 14 green sterile towels<br>19 sterile surgical gloves<br>14 non-sterile gloves<br>13 small sterile wraps<br>9 adhesive backings | Landfill |
| Stall et al (2011) | 5 | 45 green sterile towels (9)<br>16 sterile surgical gloves (3.2)<br>5 disposable surgical gowns (1)<br>4 inner wrapper surgical gloves (0.8)<br>2 lengths tubing (0.4)<br>1 small unsterile towel (0.2) | 29 green sterile towels (30 to 43)<br>41 sterile surgical gloves (37 to 52)<br>5 disposable surgical gowns (4 to 8)<br>64 plastic wrappers (59 to 73)<br>10 vinyl gloves (0 to 29)<br>5 disposable surgical drapes (2 to 8)<br>3 disposable table covers (1 to 4) | Landfill |

**Table VI.** Summary of carbon emissions.

| Article (year) | Setting | Database used | Functional unit | Cases | Findings |
|---|---|---|---|---|---|
| Baxter et al (2021) | Intraoperative (hand surgery) | EIO-LCA | 10 items across 3 types of procedures (hand drape; other drape; blade; towels; basins; RayTec sponge; laparotomy pad; Webril undercast padding; elastic bandage; suture) | 96 (32 surgeons performing one of each: CTR; ORIF of distal radial fracture; PFTR) | $CO_2$ emission range across 32 surgeons = 7.8 to 28.8 kg<br>High-use surgeon produce 10.9 kg more $CO_2$ emission compared to lean-use surgeon |
| Curtis et al (2021) | Outpatient | UK SMMT conversion factors | Outpatient clinic appointment, including travel to and from appointment | 76 (42%) F2F; 104 (58%) NF2F | Reduction of carbon emission from travel only = 563.9kg $CO_2e$ (66%)<br>Reduction of carbon emission in total (including travel and outpatient emission) = 5,846 $CO_2e$ (58%) |
| Leiden et al (2020) | Intraoperative (spinal surgery) | Umberto NXT, Ecoinvent 3.1 | Set of surgical instruments for single level lumbar fusion (reusable vs disposable) | 2 single-level lumbar fusion | Disposable set had lower environmental impact than reusable set (approximately 45% to 85% environmental advantage in all impact categories compared to reusable set; overall aggregated single-score indicator 75% benefit compared to reusable set)<br>Steam sterilization for reusable set has higher carbon emissions than $^{60}Co$ sterilization for disposable set |

CO2, carbon dioxide; $^{60}Co$, cobalt-60 (gamma radiation); CO2e, carbon dioxide equivalents; CTR, carpal tunnel release; EIO-LCA, Economic Input-Output Life Cycle Assessment; F2F, face-to-face; LCA, life-cycle assessment; NF2F, non-face-to-face; ORIF, open reduction and internal fixation; PFTR, primary flexor tendon release; SMMT, Society of Motor Manufacturers and Traders.

**Table VII.** Quantified water wastage and time taken for hand decontamination.

| Article (year) | Type of scrub used | Method of scrub (n) | Quantified wastage | Findings |
|---|---|---|---|---|
| Potgeiter et al (2020) | Water and soap: 4% chlorhexidine gluconate soap + water<br>Alcohol scrub: 0.5% chlorhexidine + 70% alcohol | Standard (2)<br>Alcohol (18)<br>Scrub nurse-assisted (12)<br>Self-wash (12) | Average litres per scrub:<br>Standard: 5.65<br>AS: 0.82<br>SN: 2.29<br>SW: 1.93 | All interventions significantly less water than baseline ($p < 0.001$)<br>AS significantly less water than SN (1.44 l; 63% less; $p = 0.033$)<br>AS less water than SW (1.11 l; 58% less; $p > 0.05$)<br>No significant difference between SN and SW |
| | | | Average seconds per scrub:<br>Standard: 163.5<br>AS: 32.8<br>SN: 120.8<br>SW: 160.3 | AS significantly less scrub time than all other categories ($p < 0.001$ for baseline and SW; $p = 0.002$ for SN): 130.7 sec (80%) less than baseline ($p < 0.001$); 127.5 sec (80%) less than SW ($p < 0.001$); 88 sec (73%) less than SN ($p = 0.002$)<br>SN less than SW but not statistically significant |

AS, alcohol scrub; SN, scrub nurse-assisted; SW, self-wash.

## Discussion

This is the first scoping review of its kind to assess the impact of sustainable practices within orthopaedic surgery. This is a growing area of interest, albeit with limited evidence.

**Table VIII.** Barriers to environmentally sustainable changes in orthopaedic surgery.

| Article | Lack of understanding of environmental impact | Lack of understanding of benefits of sustainable practices | Lack of training or knowledge | Lack of appropriate infrastructure | Lack of incentive | Resistance to change | Unclear guidelines or policies |
|---|---|---|---|---|---|---|---|
| Alam et al (2008) | | | | X | | | X |
| Baxter et al (2021) | X | X | | | X | X | |
| Curtis et al (2021) | | | | X | | | |
| De Sa et al (2016) | | | X | | | | X |
| Hennessy et al (2021) | | | X | X | | | |
| Kooner et al (2019) | | | X | | | | X |
| Lee et al (2012) | | | | X | | X | |
| Leiden et al (2020) | | | | X | | | |
| Potgeiter et al (2020) | | | | X | | X | |
| Shinn et al (2017) | X | X | | X | X | | X |
| Southorn et al (2013) | | X | X | | | | |
| Stall et al (2011) | X | X | X | X | | | |
| Thiel et al (2017) | | | | | | X | |

**Waste management - disposal and recycling.** Waste management is a prevalent issue. Most studies classified waste differently, likely due to varying institutional policies with no clear universal classification of waste, thereby resulting in varying proportions of waste across the studies. The highest proportion of hazardous waste reported in our scoping review (46.8%) exceeds the 15% reported by the WHO,[52] which is detrimental to the environment.

Up to 80% of waste generated during the perioperative period occurs prior to the patient entering the OR.[23,27] Furthermore, up to 40% of regulated OR waste is from packaging material,[53] which if correctly segregated, can potentially be recycled safely.[54] Six studies reported recycling streams; however, three of these did not include paper or cardboard,[18,42,43] and no studies reported recycling metals or glass. According to Rizan et al,[19] the carbon footprint generated from recyclable waste was lowest (21 kg to 65 kg $CO_2e$) compared to non-hazardous waste (172 kg to 249 kg $CO_2e$) and hazardous waste (569 kg 1,074 kg $CO_2e$). Additionally, metal and glass can be recycled unlimited times without affecting quality.[13,22]

THA and TKA generated the highest amount of waste per procedure (12.6 kg and 13.1 kg, respectively),[18,39,40,45] with up to 33.5% of this being potentially recyclable.[44] In 2020, despite the impact of the COVID-19 pandemic on elective hip and knee arthroplasties in England, 54,858 THAs and 50,904 TKAs were performed.[55] This would have generated a total annual waste of 692,483 kg for THA and 666,842 kg for TKA, of which 455,374 kg would be potentially recyclable.

**Waste management - blue wrap and surgical linen.** Blue wrap was classified as a separate waste stream, and only two studies reported recycling this.[18,42] Interestingly, both were conducted in Canada, but did not clarify how this was recycled. Blue wrap currently accounts for approximately 19% of OR waste, is non-biodegradable, and not currently widely recycled.[7,17] Being able to readily recycle blue wrap would be beneficial to orthopaedic surgery, as many procedures use multiple surgical trays wrapped in layers of blue wrap per case. In fact, studies have demonstrated that this can range from three trays per arthroscopy to 14 trays per THA.[56,57]

Only two studies reported reusing surgical linens and did not include this in their waste measurements.[18,42] The age-old discussion of reusable versus disposable surgical gowns and drapes remains inconclusive, as there is currently no statistical difference in the rate of surgical site infections (SSI) between reusable and disposable surgical drapes.[58–60] However, the environmental advantages concluded by Vozzola et al[61] demonstrated that reusable gowns consumed 28% less energy, 41% less water, and generated 30% fewer GHG emissions and 93% less solid waste than disposable gowns.

**Carbon emissions.** Three studies focused on carbon emissions. The findings from Baxter et al[48] provided only a limited measurement of the carbon emissions generated from ten items across three types of procedures. Even then, the findings are subject to recall bias, as this retrospective study relied on surgeons' abilities to recall the number of items used during their procedures.

Leiden et al[50] concluded that $^{60}$Co-gamma radiation had a lower energy demand and negligible environmental impact. However, it is worth noting that $^{60}$Co-gamma radiation requires stringent handling safety regulations, and facilities are usually located away from hospital ground, consequently generating carbon emissions from the transportation of equipment to and from these facilities.[50]

Neither Baxter et al[48] nor Leiden et al[50] factored in carbon emissions generated by energy used to maintain the HVAC systems or from anaesthetic activities. A recent systematic review found that two areas contributing the

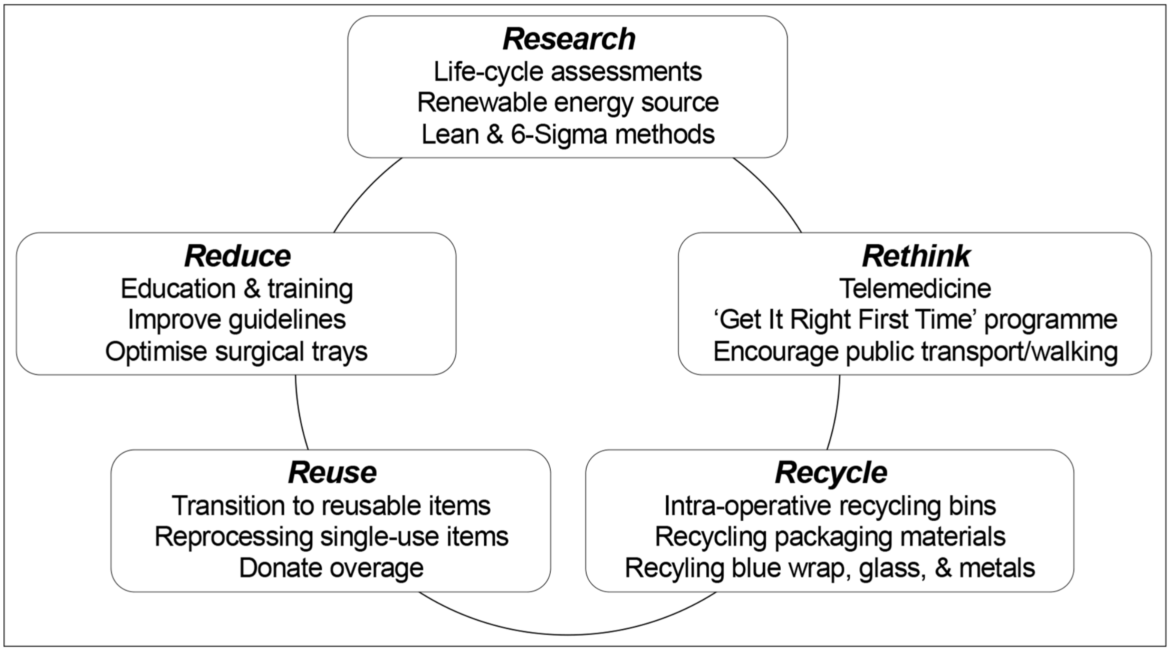


**Fig. 4**

Summary of actions for change using the '5 R' strategy.

most to carbon emissions within ORs were energy use and procurement of consumables.[9] In fact, an average operation in the UK generates approximately 173 kg $CO_2e$, and the NHS supply chain is responsible for up to 59% of the total NHS carbon footprint.[9,12,28]

Telemedicine is the use of information and communication technologies to deliver and facilitate healthcare services.[62] This is becoming more commonplace in orthopaedic surgery, with its use further accelerated by the COVID-19 pandemic.[63–65] The carbon emissions reduced through minimizing travel are demonstrated by Curtis et al[49] and supported by Purohit et al.[66] Telemedicine can be a valuable asset in supporting a more environmentally sustainable speciality; however, this cannot replace all orthopaedic appointments.

**Water usage.** Alcohol hand rubs are currently supported by the WHO and National Institute for Health and Care Excellence guidelines, but must be preceded by a standard soap and water scrub for the first operation of the day, provided that hands are not visibly soiled between subsequent operations.[67,68] Alcohol preparations should also contain 60% to 90% alcohol to be considered effective for hand decontamination.[69,70] Studies have further conferred that there was no significant difference in SSI rates between alcohol hand rubs and other methods of hand-washing.[71–73] Potgeiter et al[51] reported significantly less water and time being wasted when using alcohol hand rubs. This study also demonstrated that switching taps off while not in use during the scrub significantly reduced water usage by 59.5% to 65.8%, compared to when taps were running constantly throughout the scrub. These simple actions resulted in extrapolated water savings of up to 180,000 l, can be easily implemented across all orthopaedic theatres, and would save vast amounts of water.

**Barriers to change.** The initiation and implementation of environmentally sustainable changes within orthopaedic surgery is not without its barriers, as described by all 13 studies, and has also been echoed by other authors describing similar issues.[21,53,74,75] A lack of infrastructure was most quoted, which encompassed issues such as inadequate waste collection, disposal, transportation, containment, or sorting and recycling facilities. In the UK, fewer than 10% of hospitals have implemented meaningful basic recycling programmes, which is lower compared to other countries such as the USA (50%) and Australia (80%).[39] OR staff also attributed poor waste segregation to a lack of knowledge of the classification of waste, or to unclear waste disposal guidelines.

Changes to practice will inevitably invoke concern and resistance from staff. Baxter et al[48] ascribes this to reasons such as fear of losing familiarity with their environment, poorer patient outcomes, reduced OR efficiency, and increased workload. However, a recent survey of surgeons in the UK and Ireland revealed that 56% of respondents have seen changes implemented in the workplace, 85% were eager to engage in education and training programmes, and 63% were willing to participate in research or quality improvement work related to this.[75]

**Actions for change.** The '5 R' strategy of improving environmental sustainability has a wide role to play within orthopaedic surgery. All included studies have recommended environmentally sustainable practices that can be incorporated within orthopaedic surgery (Figure 4).

Education and formal training programmes, focusing on the correct segregation of waste and the benefits of environmental sustainability within orthopaedic surgery, have been shown to reduce the proportion of biohazardous waste generated and increase recycling rates within the OR.[13,20,39,76] This should also be partnered with improvements in waste segregation policies or guidelines within ORs, and to clarify the definitions of waste streams.[39–42] Intraoperative recycling bins or waste sorting facilities can help promote recycling practices.[40,41,43,45] Hospitals can also partner with local waste management companies to establish means of recycling less common items such as blue wrap, metals, and glass.[40] Implant manufacturing companies can also participate in this effort by reducing the amount of packaging materials used, and opting for more environmentally friendly or recyclable material.[18,39]

The optimization of surgical trays or regularly updating surgeons' crib sheets can reduce the amount of waste and overage generated.[18,43,48,50] Transitioning to reusable items, such as surgical gowns, drapes, or pneumatic tourniquets, or reprocessing single-use orthopaedic devices, such as arthroscopic shavers, wands, saw blades, or burrs, can reduce the amount of waste generated.[18,23,42,48] Overage from the orthopaedic ORs can also be donated to organizations that supply them to developing nations or areas requiring humanitarian aid.[18,20,22] Promoting the use of LCA methodology is critical in informing environmentally sustainable decision-making.[18,40,50]

Strategies to reduce resource consumption in orthopaedic surgery can greatly benefit the environment. Conscious actions, such as switching water taps off when not in use, or using alternative hand decontamination methods with lower water consumption, can significantly reduce water wastage.[51] To reduce energy consumption, idle or unused ORs can be powered down. Additionally, hospitals can invest in upgrading existing HVAC systems to newer and more efficient models.[8] Embracing new technology, such as telemedicine or electronic medical systems, can also reduce carbon emissions.[49,77]

Further research is needed to identify safe and efficient ways of implementing environmentally sustainable changes within orthopaedic surgery, while still safeguarding high-quality care and good patient outcomes. A recent systematic review has demonstrated that adopting sustainable methods can improve both OR efficiency and postoperative care.[78,79] This is further supported by the novel pilot Getting It Right First Time (GIRFT) approach in orthopaedic surgery, which successfully improved efficiency, savings, and, ultimately, patient care across the UK.[80,81] As a result, between 2014 and 2019, over 380,000 inpatient bed days were reduced from length of stays, 5,000 emergency readmissions were prevented, and 49,000 unnecessary procedures were avoided, equating to a reduction of approximately 26.5 kt$CO_2$e.[28]

This scoping review has several limitations that must be considered. The environmental impact of waste management investigated by various studies revealed varying practices of waste segregation across the different institutions. Most of the studies focused only on waste management within orthopaedic surgery, with the remaining studies looking at different aspects of orthopaedic surgery. The differences in sample sizes and designs between these studies, therefore, make the comparison of results challenging. Due to the heterogeneity across the studies, a meta-analysis of the results was not feasible.

This has further emphasized the gap in the literature outside the scope of waste management, which suggests that future studies are necessary to explore the environmental impact of other facets of orthopaedic surgery. Many studies investigated either individual or a select few subspecialties within orthopaedic surgery. In addition, not all orthopaedic procedures included in the studies were specified. As a result, this may not be a true reflection of environmental sustainability across the whole of orthopaedic surgery. The studies included in this scoping review did not comment on the safety and efficacy of environmentally sustainable practices, nor were there any studies investigating the long-term benefits, which suggests that further studies in these areas are necessary.

Existing studies on environmental sustainability in orthopaedic surgery have uncovered a wide potential for change with the initiatives demonstrating impacts in their respective areas. However, this has also revealed the need for further higher-quality and large-volume studies on the cumulative carbon footprint of orthopaedic surgery, and to ensure that environmentally sustainable changes are able to maintain a high standard of patient care. It is evident that environmental sustainability in orthopaedic surgery is becoming an increasingly discussed topic, with efforts aiming to slow or even reverse the effects of climate change. The idea of a 'greener' speciality is surely within reach, where changes should start with small steps, but most certainly require the collaboration of all involved to preserve these changes for the benefit of our environment.

## Take home message

- Orthopaedic surgery remains a contributor to the carbon footprint of healthcare on the environment, but environmental sustainability within orthopaedic surgery is becoming an increasingly discussed topic with evidence of 'greening' efforts taking place.
- The most prevalent issue identified through this systematic review was the management of waste within orthopaedic operating theatres.
- This study has revealed the need for higher quality and larger-volume studies focusing on the cumulative carbon footprint of orthopaedic surgery across the specialty, and that promoting and implementing environmentally sustainable changes require collaboration.

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## Supplementary material

Search strategies using the Healthcare Database Advanced Search for EMBASE and Medline databases, and search strategy for PubMed database

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