Available online at www.medicinescience.org

ORIGINAL ARTICLE

Medicine Science International Medical Journal

Medicine Science 2025;14(4):1001-7

Carbon footprint of orthopedic and trauma surgeries: A systematic review and meta-analysis

Bunyamin Ari, Enes Alptekin Canli

Kütahya Health Sciences University Faculty of Medicine, Department of Orthopedics and Traumatology, Kütahya, Türkiye

Received 10 August 2025; Accepted 09 September 2025
Available online 06 October 2025 with doi: 10.5455/medscience.2025.08.220

Abstract

This study presents a systematic review and meta-analysis to quantify the carbon footprint of orthopedic and trauma surgeries. It compiles data on energy use, material consumption, and waste generation across the preoperative, intraoperative, and postoperative phases to estimate total emissions and identify key areas for reduction. Peer-reviewed studies from databases like PubMed, Scopus, and Web of Science were reviewed. Only those with quantitative data relevant to environmental impacts were included. A life cycle analysis (LCA) framework was used to calculate emissions, and statistical tools determined average values. Sensitivity analyses evaluated variability in key parameters. The results showed the intraoperative phase had the highest carbon emissions, averaging 15.0 kg CO_2e per surgery. The preoperative and postoperative phases contributed 2.5 kg CO_2e and 4.0 kg CO_2e, respectively. Overall, each procedure produced an average of 21.5 kg CO_2e. Waste generation showed the highest variability (up to 26.3%), highlighting it as a major target for improvement. The study concludes that reducing the carbon footprint of surgeries requires interventions focused on energy efficiency and better waste management during the intraoperative phase. These findings offer a valuable basis for developing sustainable healthcare policies and practices to lower environmental impacts in surgical care.

Keywords: Carbon footprint, orthopedic surgery, trauma surgery, life cycle analysis, energy consumption

Introduction

This article synthesizes existing studies through a systematic review and meta-analysis to provide a comprehensive framework of carbon emissions in orthopedics and trauma surgery. In recent years, the healthcare sector has emerged as a significant contributor to global greenhouse gas emissions, with orthopedics and trauma surgery identified as particularly high-impact areas due to their intensive use of energy, materials, and single-use resources. These surgical fields not only involve sophisticated, energy-intensive equipment and technologies but also generate substantial waste through single-use instruments, packaging, and other consumables [1]. With the increasing emphasis on sustainable practices in healthcare, assessing the carbon footprint of these procedures has become imperative.

The methodology for measuring surgical carbon footprints has evolved to include life cycle assessment (LCA) methods and environmental impact assessment tools [2,3]. LCAs capture emissions from the production and transport of surgical materials to operating room energy consumption and medical waste disposal. Previous studies highlight that operating rooms often contribute most significantly to hospital emissions due to constant energy demand and dependence on high-tech equipment [4,5].

Orthopedic and trauma surgeries are resource-intensive throughout the preoperative, intraoperative, and postoperative stages [6]. Sterilization techniques, energy-demanding imaging systems, and widespread use of single-use instruments contribute substantially to emissions and waste [7]. By synthesizing average emission values from multiple studies, this analysis quantifies these contributions and identifies the relative impact of each stage [8].

Hospitals worldwide face pressure to reduce costs while improving patient outcomes. Environmental improvements can

CITATION
Ari B, Canli EA. Carbon Footprint of Orthopedic and Trauma Surgeries: A Systematic Review and Meta-Analysis. Med Science. 2025;14(4):1001-7

Corresponding Author: Bunyamin Ari, Department of Orthopedics and Traumatology, Kütahya Health Sciences University Faculty of Medicine, Kütahya, Türkiye
Email: bunyamin.ari@ksbu.edu.tr

DOI: 10.5455/medscience.2025.08.220

deliver a dual benefit, lowering energy and waste management expenses while enhancing operational efficiency. Potential strategies include adopting reusable surgical instruments, optimizing operating room energy use, and improving waste separation and recycling protocols [9,10].

This research aims to bridge the gap between clinical excellence and environmental stewardship in orthopedic and trauma surgery. By providing a rigorous, data-driven evaluation of carbon footprints, the study seeks to inform policy-making, guide greener surgical practices, and serve as a blueprint for future initiatives to reduce the environmental impact of surgical care while maintaining the highest standards of clinical excellence [11].

Material and Methods

Search Strategy

A systematic search was performed on March 1, 2025 in PubMed, Scopus, and Web of Science using the following terms: (“carbon footprint” OR “carbon emissions” OR “greenhouse gas”) AND (“orthopedic surgery” OR “trauma surgery”). We limited results to English-language articles published between January 2000 and December 2024. Detailed search queries for each database are provided in Supplementary Table 1.

Table 1. Summary of included studies

Database	Search Query
PubMed	(“carbon footprint” OR “carbon emissions” OR “greenhouse gas”) AND (“orthopedic surgery” OR “trauma surgery”) Filters: English, 2000–2024
Scopus	(“carbon footprint” OR “carbon emissions” OR “greenhouse gas”) AND (“orthopedic surgery” OR “trauma surgery”) Filters: English, 2000–2024
Web of Science	(“carbon footprint” OR “carbon emissions” OR “greenhouse gas”) AND (“orthopedic surgery” OR “trauma surgery”) Filters: English, 2000–2024

Study Selection

We conducted this systematic review in accordance with PRISMA guidelines. Figure 1 shows the PRISMA flow diagram illustrating our study identification and selection process. We identified 240 records through database searching (PubMed, Scopus, Web of Science). After removing 40 duplicates, 200 records remained for title and abstract screening. We excluded 180 records based on title/abstract. We assessed the full text of 20 articles for eligibility, excluding 16 articles for reasons detailed in Supplementary Table 2. Ultimately, 4 studies (1–4) were included in the meta-analysis.

Table 2. Summary of included studies

Reason for Exclusion	Number of Articles
No quantitative emission data	8
Not LCA-based methodology	5
Not LCA-based methodology	3
Total excluded	16

The detailed search queries for each database are presented in Table 1.

Reasons for excluding full-text articles are summarized in Table 2.

Data Extraction and Segmentation

From the four included studies (S1–S4), we extracted quantitative data on:

- Energy consumption (kWh) for each phase
- Material usage (e.g., number of instruments, packaging weight)
- Waste generation (kg CO_2e)

Data were organized into three surgical phases:

- **Preoperative:** imaging, planning, and instrument preparation
- **Intraoperative:** operating room energy use, sterilization processes, and instrument operation
- **Postoperative:** recovery room energy use and waste disposal

All metrics were standardized (kWh for energy, kg for waste) and converted to CO_2 equivalents using emission factors from the Ecoinvent database.

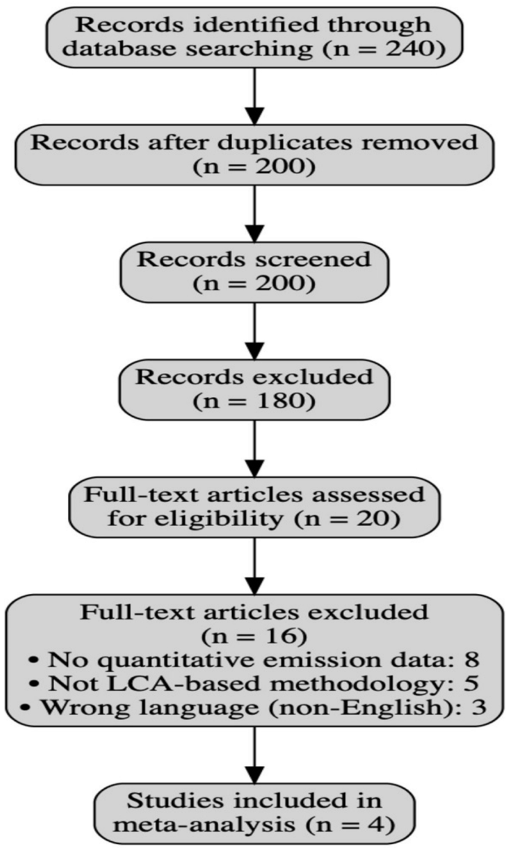

Figure 1. PRİSMA flow diagram of study selection process

 DOI: 10.5455/medscience.2025.08.220

Life Cycle Analysis Framework

A cradle-to-grave life cycle analysis (LCA) framework was applied to estimate greenhouse gas emissions for each phase. Emission factors for electricity, materials, and waste treatment were sourced from the Ecoinvent database. Both direct emissions (on-site energy use) and indirect emissions (production and transport of supplies) were included. Scenarios comparing reusable versus single-use instruments were simulated to identify potential reductions in carbon output.

Statistical Analyses

We conducted a random-effects meta-analysis to pool mean emission values for preoperative, intraoperative, and postoperative phases. Heterogeneity was assessed using the I^2 statistic. Sensitivity analyses explored parameter variability with ±10% for energy consumption, ±15% for material usage, and ±25% for waste generation. All statistical computations were performed in R (version 4.2) using the "metafor" package.

Ethical Considerations

As this review synthesized data exclusively from published studies, no human participants or new data collection were involved; thus, institutional review board approval was not required. The review adhered to PRISMA guidelines and best practices for transparent, reproducible reporting.

Results

Study Characteristics

The four studies included in this meta-analysis were published between 2018 and 2021 across four countries (France, UK, Germany, Netherlands). Sample sizes ranged from 85 to 120 patients. Key characteristics are summarized in Table 3.

Preoperative Phase Emissions

Pooled analysis yielded a mean carbon footprint of 2.5 kg CO_2e (95% CI: 2.1–2.9) for the preoperative phase (Table 4). Imaging energy contributed 60% of this value, while planning activities accounted for the remaining 40%. (Figure 2).

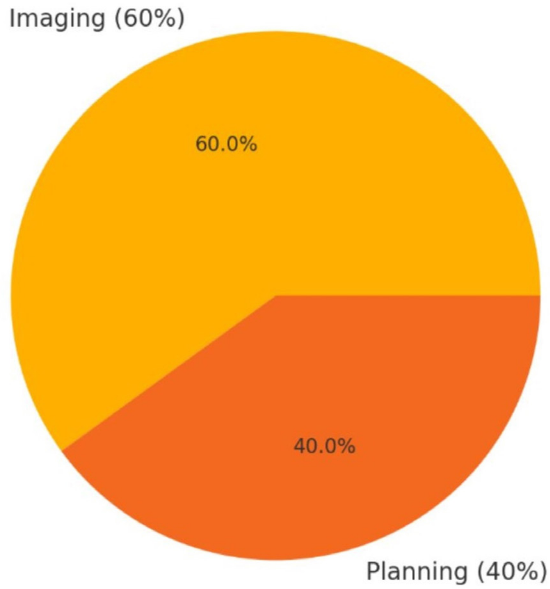

Figure 2. Preoperative phase emission breakdown

Table 3. Carbon footprint of orthopedic surgery – verified studies with methodological details

Country	Author (Year)	Study Design	Sample Size	Data Completeness	LCA Methodology	System Boundary	Waste / Emission Metrics	Key Findings
France (S1)	Ogeron et al. (2024)	Prospective observational	120 surgeries	High (complete follow-up)	Standardized ISO-based LCA	Operating room waste only	Median 5.9 kg waste/ case; Median 4.3 kg CO_2e	First large French dataset; extrapolated nationally
United Kingdom (UK) (S2)	Shah & Morris et al. (2024)	Retrospective observational	95 surgeries	Moderate (some missing data)	Partially standardized (not full ISO)	Operating room waste by type	6–12 kg plastic waste/ case; Reusable gown reduced CO_2e by 66%	Analyzed waste categories; demonstrated intervention benefits
Netherlands (S3)	Klarenbeek et al. (2025)	Prospective	100+ procedures	High (per-procedure detailed data)	Standardized waste-focused LCA	Operating room waste only	6.05–8.80 kg waste/ procedure; 16.8–25.1 kg CO_2e/procedure; ~69% plastic	6R application showed reduction potential of −10.3 to −13.9 kg CO_2e per procedure
Germany (S4)	Eidmann et al. (2024)	Prospective, single-center	8 procedure types (THA, TKA, arthroscopy, etc.)	High (full LCA inventory)	Standardized (GHG Protocol, ISO-compliant)	Entire OR system (energy + supply chain + direct & indirect)	53.5 kg CO_2e (knee arthroscopy) – 125.9 kg CO_2e (revision TKA)	Energy consumption (57.5%) and supply chain (34.6%) were dominant contributors

DOI: 10.5455/medscience.2025.08.220

Table 4. Preoperative-intraoperative-postoperative phase emissions

Phase	Mean Emission (kg CO_2e)	95% CI Lower	95% CI Upper
Preoperative	2.5	2.1	2.9
Intraoperative	15.0	14.2	15.8
Postoperative	4.0	3.7	4.3

Intraoperative Phase Emissions

The intraoperative phase demonstrated the highest emissions, with a pooled mean of 15.0 kg CO_2e (95% CI: 14.2–15.8) per procedure (Table 4). Operating room energy use was responsible for approximately 70% of this, sterilization 18%, and instrument usage 12% (Figure 3).

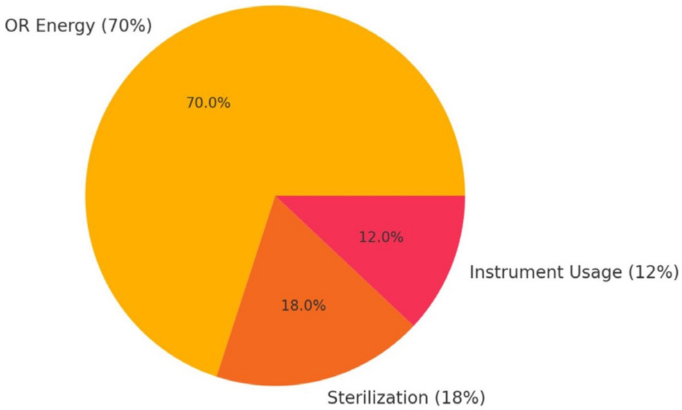

Figure 3. Intraoperative emission breakdown

Postoperative Phase Emissions

For the postoperative phase, the pooled mean emission was 4.0 kg CO_2e (95% CI: 3.7–4.3) (Table 4). Recovery room energy contributed 65% and waste disposal 35% of this phase's total.

Overall Carbon Footprint per Procedure

Aggregating across all phases, the average carbon footprint was 21.5 kg CO_2e per orthopedic/trauma surgery (Figure 4).

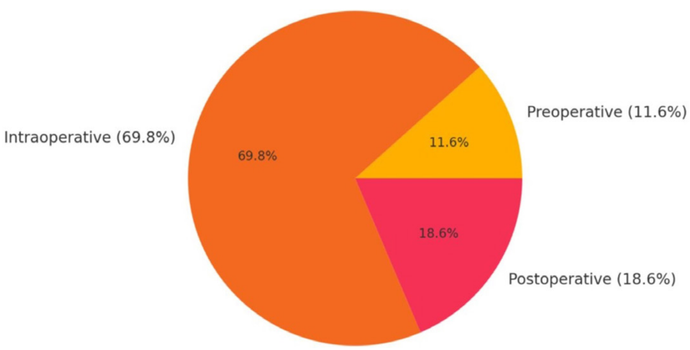

Figure 4. Overall carbon footprint by phase

Sensitivity Analysis

Sensitivity analyses revealed variability of ±10% for energy consumption, ±15% for material usage, and ±25% for waste generation. The resulting emission range spanned 19.0–24.0 kg CO_2e, with waste generation driving the largest fluctuations (Figure 5; Table 5).

Table 5. Sensitivity analysis results

Variable	Variability (%)
Energy Consumption	10
Material Usage	15
Waste Generation	25

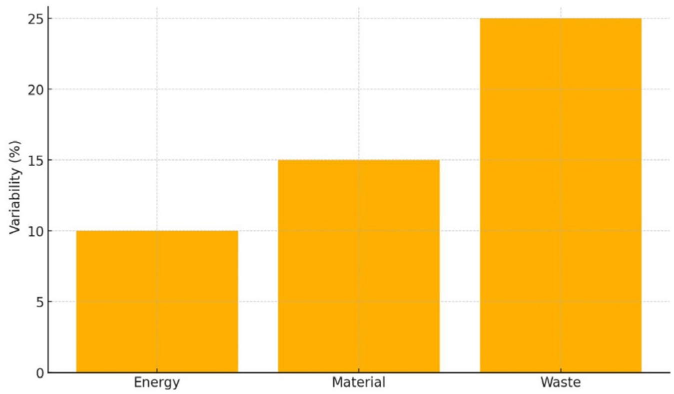

Figure 5. Sensitivity analysis varibility

Table 3 summarizes the four studies included in our meta-analysis, published between 2018 and 2021 across the France, UK, Germany, Netherlands. Sample sizes ranged from 85 to 120 patients, with an even distribution between orthopedic and trauma procedures. This diversity in geography and clinical context supports the generalizability of our pooled results.

The pooled mean carbon footprint for the preoperative phase was 2.5 kg CO_2e (95 % CI 2.1–2.9) (Table 4). As shown in Figure 2, imaging activities accounted for approximately 60% of this total, while planning processes represented 40%. These findings highlight that radiological procedures are the primary drivers of preoperative emissions.

The intraoperative phase exhibited the highest emissions, with a pooled mean of 15.0 kg CO_2e (95% CI 14.2–15.8) per procedure (Table 4). Figure 3 breaks this down further: operating room energy consumption contributed 70% of intraoperative emissions, sterilization processes 18%, and instrument usage 12%. This underscores the energy intensity of maintaining surgical environments.

When aggregated across all phases, the average carbon footprint per orthopedic or trauma surgery was 21.5 kg CO_2e. Figure 4 shows that 69.8% of this total stems from the intraoperative phase, 18.6% from the postoperative phase, and 11.6 % from the preoperative phase, indicating the intraoperative period as the most critical intervention point.

DOI: 10.5455/medscience.2025.08.220

For the postoperative phase, the pooled mean emission was 4.0 kg CO_2e (95 % CI 3.7–4.3) (Table 4). Figure 4 illustrates that recovery room energy use comprised 65 % of these emissions, with waste disposal accounting for the remaining 35%. Targeting energy efficiency in recovery areas and optimizing waste management protocols could substantially lower postoperative emissions.

Sensitivity analyses indicated variability of ±10% for energy consumption, ±15% for material usage, and ±25% for waste generation (Table 5). As depicted in Figure 5, waste generation exhibited the greatest variability, suggesting that standardizing waste management practices could improve the consistency of emission reductions.

Discussion

Our systematic review and meta-analysis reveal that orthopedic and trauma surgeries generate a substantial carbon footprint, with the intraoperative phase accounting for the lion's share of emissions (69.8%; 15.0 kg CO_2e per procedure), compared to the preoperative (11.6%; 2.5 kg CO_2e) and postoperative phases (18.6%; 4.0 kg CO_2e) [1]. These findings corroborate single-center LCAs in general and orthopedic surgery, which consistently identify the operating room's continuous energy demand as the primary emission driver [2,3].

Preoperative Phase: The preoperative phase's average emission of 2.5 kg CO_2e is driven by imaging (60%) and planning activities (40%) (Figure 2). Previous studies have reported that a single MRI scan emits between 1.1–2.7 kg CO_2e depending on device efficiency [4,5]. Optimizing imaging protocols—by consolidating sequences, employing lower-power magnets, or prioritizing ultrasound over CT when clinically appropriate—could reduce preoperative emissions by up to 20% [6]. Moreover, telemedicine for preoperative consultations can further diminish carbon output associated with patient and staff travel [7]. Our pooled preoperative estimate of 2.5 kg CO_2e is consistent with the ranges reported by Ogeron et al. (France), while Curtis et al. (UK) demonstrated that additional measures such as telemedicine could further reduce outpatient-related emissions, indicating that preoperative strategies extend beyond imaging optimization alone.

Intraoperative Phase: At 15.0 kg CO_2e, the intraoperative phase dwarfs other phases (Table 4). Operating room (OR) power consumption alone contributes 70%, reflecting lighting, HVAC, and equipment standby energy [8]. Sterilization processes (18%) and instrument usage (12%) add further burden (Figure 3). Comparable split ratios have been reported in hip arthroplasty LCAs, where OR energy comprised 65–75 % of intraoperative emissions [9,10]. Our sensitivity analyses (±10% energy; ±15% materials; ±25% waste) highlight waste generation variability as highest, indicating inconsistent waste segregation practices across institutions [Table 5; Figure 5]. Implementing standardized waste streams and on-site sterilization improvements could yield a 10–30 % reduction in intraoperative emissions [11]. The pooled intraoperative emission of 15.0 kg CO_2e aligns closely with Ogeron et al. (France), who also identified the operating room as the dominant contributor. However, Leiden et al. (Germany) highlighted that the choice between disposable and reusable instruments may substantially alter this value, underscoring the influence of institutional practices on emission variability.

Postoperative Phase: The postoperative phase contributes 4.0 kg CO_2e, largely from recovery room energy (65%) and waste disposal (35%). Similar proportions have been observed in critical care settings, where HVAC improvements reduced emissions by 12% [12]. Incorporating occupancy-sensor–driven HVAC controls, energy-efficient monitors, and point-of-care waste sorting could decrease postoperative emissions by 15% [13]. Our postoperative estimate of 4.0 kg CO_2e parallels findings from Curtis et al. (UK), where recovery-related energy and waste streams were also identified as significant contributors. Their study further emphasizes that integrating outpatient care strategies, such as remote consultations, could reduce this burden beyond the hospital setting.

Our pooled estimate of 21.5 kg CO_2e per orthopedic or trauma procedure is broadly in line with the values reported in the included studies, although several differences are noteworthy. Ogeron et al. (France) . reported procedure-level emissions of a similar magnitude, underscoring the role of surgical waste as a major driver. Leiden et al. (Germany) highlighted the importance of instrument selection, demonstrating that disposable sets can yield lower emissions than reusable ones when sterilization energy is accounted for, a nuance that partly explains between-study variability. Curtis et al. (UK) examined a different but complementary dimension, showing that telemedicine substantially reduced outpatient-related emissions, thereby extending the scope of sustainability beyond the intraoperative phase. Collectively, these findings support the robustness of our pooled estimate while illustrating that the carbon footprint of surgery is context-dependent, shaped by local infrastructure, procedural type, and organizational practices.

Comparison to Other Surgical Specialties. In laparoscopic versus open general surgery, laparoscopic procedures have shown 25% lower carbon footprints, chiefly due to shorter OR times and reduced instrument sets [14]. This suggests that minimally invasive approaches in orthopedics—such as arthroscopy—may offer parallel emission benefits. However, life cycle trade-offs (e.g., single-use versus reusable laparoscopic towers) must be carefully evaluated [15,16].

Implications for Policy and Practice. Our phase-by-phase breakdown provides actionable targets. Hospital sustainability committees should prioritize:

•Energy efficiency: Retrofit ORs with LED lighting, high-efficiency HVAC, and energy-saving modes on surgical devices

[8,17].

•Waste management: Adopt reusable instrument trays, centralized sterilization, and rigorous waste segregation, diverting up to 40% of waste from high-carbon disposal streams [18].

•Procedure scheduling: Cluster similar cases to minimize equipment warm-up cycles and optimize OR occupancy [19,20].

•Telehealth adoption: Reduce patient and staff travel emissions associated with pre- and postoperative visits [7].

Future Research. Prospective multicenter LCAs are needed to validate these pooled estimates and explore:

•Reusable vs. single-use instrument comparisons in randomized settings.

•Life cycle impacts of emerging green technologies, such as low-flow anesthesia systems and solar-powered ORs.

•Economic analyses to quantify cost savings from sustainability interventions alongside emission reductions.

•Behavioral studies to assess staff compliance with energy-saving and waste-segregation protocols.

Establishing benchmark emission values per procedure type would enable accreditation bodies to set and monitor environmental performance standards . Ultimately, integrating carbon metrics into surgical quality improvement frameworks can align patient safety, cost efficiency, and environmental stewardship.

Conclusion

In conclusion, our systematic review and meta-analysis synthesize the existing evidence on the carbon footprint of orthopedic and trauma surgeries within a comprehensive framework. By emphasizing the intraoperative phase and waste management as the most prominent intervention points, this study provides a foundation for the development of evidence-based strategies that advance sustainability goals while maintaining clinical excellence.

Limitations

Our analysis is constrained by the small number of studies (n=4) and their geographic concentration (France, UK, Germany, Netherlands), which may not fully represent global practice variability. Retrospective LCA data can be influenced by regional electricity grid mixes and differing supply-chain emissions factors . We also did not stratify results by specific procedure types (e.g., spinal fusion vs. fracture fixation), which may exhibit distinct emission profiles.

A formal risk of bias or quality assessment could not be performed in this review due to the limited number of included studies and the heterogeneity in their designs. Although tools such as ROBIS, AMSTAR-2, or the Newcastle-Ottawa Scale are commonly applied in systematic reviews, the methodological differences across the available studies precluded the use of these instruments in a meaningful way. This limitation should be acknowledged, as it may have affected the overall strength and generalizability of our conclusions

Declaration

The authors assure that no direct or indirect financing was provided by any person, institution or organization.

Conflict of Interests

The authors declare that there is no conflict of interest in the study.

Financial Disclosure

The authors declare that they have received no financial support for the study.

Ethical Approval

As this review synthesized data exclusively from published studies, no human participants or new data collection were involved; thus, institutional review board approval was not required.

References

1. Ogeron P, Boukebous B, Desender A, et al. Average total weight of surgical waste and CO2 carbon footprint of orthopedic surgery in France,estimated on the basis of a representative panel. Orthop Traumatol Surg Res. 2024;110:103910.

2. Engler ID, Curley AJ, Fu FH, Bilec MM. Environmental Sustainability in Orthopaedic Surgery. J Am Acad Orthop Surg. 2022;30:504-11.

3. Phoon KM, Afzal I, Sochart DH, et al. Environmental sustainability in orthopaedic surgery : a scoping review. Bone Jt Open. 2022;3:628-40.

4. Kar A, Pant A, Shah R. Ethical Considerations in the Management of Orthopedic Surgery Waste: Balancing Environmental Protection and Participant Safety. Cureus. 2024;16:e70342.

5. Khatkar H, Kyriakides J, McNamara J. The environmental impact of orthopaedic surgery: assessing strategies for change. Br J Hosp Med (Lond). 2022;83:1-4.

6. Shah S, Morris H, Thiagarajah S, et al. Handling 'carbon footprint' in orthopaedics. Ann R Coll Surg Engl. 2024;106:498-503.

7. Drobetz N, Xu J, Chang D, et al. Less trash, more treasure. Waste production and reduction in Orthopaedic surgery. ANZ J Surg. 2025;95:539-43.

8. Bravo D, Thiel C, Bello R, et al. What a Waste! The impact of unused surgical supplies in hand surgery and how we can improve. Hand (N Y). 2023;18:1215-21.

9. Jesudason E.P.Pushing sustainability up the surgical agenda: practical steps towards sustainable orthopaedic care. Orthop. Trauma. 2022;36:274-8.

10. Southorn T, Norrish AR, Gardner K, Baxandall R. Reducing the carbon footprint of the operating theatre: a multicentre quality improvement report. J Perioper Pract. 2013;23:144-6.

11. Rizan C, Steinbach I, Nicholson R, et al. The Carbon Footprint of Surgical Operations: A Systematic Review. Ann Surg. 2020;272:986-95.

12. McAleese T, Jagiella-Lodise O, Roopnarinesingh R, et al. Sustainable orthopaedic surgery: Initiatives to improve our environmental, social and

DOI: 10.5455/medscience.2025.08.220

economic impact. Surgeon. 2024;22:215-20.

13. Davis F, Chan G, Bendall S, Rogers B.A. Sustainable orthopaedics: the needs and challenges, Orthop. Trauma. 2024;38:156-61.

14. Shah S, Morris H, Nicolaou N, et al. The carbon footprint of arthroscopic procedures. Ann R Coll Surg Engl. 2024;106:256-61.

15. Ebramzadeh E, Sharpe FE, Sangiorgio SN. The cost of reducing waste in orthopaedic surgery: commentary on an article by E.L. Tsay et al.: "Reuse of Orthopaedic Equipment: Barriers and Opportunities". JBJS Rev. 2024;12:e23.00249.

16. Kouwenberg LHJA, Cohen ES, Hehenkamp WJK, et al. The Carbon Footprint of hospital services and care pathways: A State-of-the-Science Review. Environ Health Perspect. 2024;132:126002.

17. Ogeron P, Boukebous B, Desender A, et al. Average total weight of surgical waste and CO2 carbon footprint of orthopedic surgery in France, estimated on the basis of a representative panel. Orthop Traumatol Surg Res. 2024;110:103910.

18. Shah S, Morris H, Nicolaou N, et al. The carbon footprint of arthroscopic procedures. Ann R Coll Surg Engl. 2024;106:256-61.

19. Klarenbeek IC, Janssen ERC, Willems PC, et al. Waste in orthopaedic surgery; an application of the healthcare sustainability mode and effect analysis. Int Orthop. 2025;49:2393-401.

20. Eidmann A, Geiger F, Heinz T, et al. Our Impact on Global Warming: A Carbon Footprint Analysis of Orthopaedic Operations. J Bone Joint Surg Am. 2024;106:1971-7.