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Environmental footprint of gastrointestinal endoscopy services: a systematic review

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Abstract:
Background – Gastrointestinal (GI) endoscopy is a significant contributor to healthcare-related climate change due to high procedure volumes, intensive decontamination processes, and reliance on single-use products. This systematic review aims to synthesize the current evidence on the environmental impact of GI endoscopy.
Methods – MEDLINE, Embase and Web of Science were systematically searched up to May 2025 for studies assessing the environmental impact of GI endoscopy. Two reviewers independently performed study selection, data extraction, and quality assessment. The PRISMA guidelines were followed.
Results – A total of 28 studies were included. Most studies assessed carbon emissions; only five studies (18%) examined environmental impacts beyond greenhouse gas emissions. The largest contributors to emissions were patient travel, energy use, and procedure-related products, while waste had limited impact. Overall, scope 3 emissions accounted for the majority of total emissions, though reporting across different emission scopes was inconsistent. In line with heterogeneity in methodology, per–procedure emissions ranged from 5.4 to 73.2 kg CO2 equivalent. Twenty-one studies (75%) were judged to have a high risk of bias.
Discussion – Current evidence on the environmental impact of GI endoscopy services is fragmented, methodologically inconsistent, and often limited in coverage. Emissions were dominated by patient travel, energy use and procedure-related products. Broader and more standardized environmental assessments are needed to guide the transition to low-carbon, sustainable GI endoscopy.

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Environmental footprint of gastrointestinal endoscopy services: a systematic review

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Author contributions:

PDS conceived the study. BV collected the data. BV, DG and CBI processed and analyzed the data. All other authors provided oversight. BV wrote the first draft of the manuscript. All authors interpreted the data and critically edited the final manuscript.

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ABSTRACT

Background

Gastrointestinal (GI) endoscopy is a significant contributor to healthcare-related climate change due to high procedure volumes, intensive decontamination processes, and reliance on single-use products. This systematic review aims to synthesize the current evidence on the environmental impact of GI endoscopy.

Methods

MEDLINE, Embase and Web of Science were systematically searched up to May 2025 for studies assessing the environmental impact of GI endoscopy. Two reviewers independently performed study selection, data extraction, and quality assessment. The PRISMA guidelines were followed.

Results

A total of 28 studies were included. Most studies assessed carbon emissions; only five studies (18%) examined environmental impacts beyond greenhouse gas emissions. The largest contributors to emissions were patient travel, energy use, and procedure-related products, while waste had limited impact. Overall, scope 3 emissions accounted for the majority of total emissions, though reporting across different emission scopes was inconsistent. In line with heterogeneity in methodology, per–procedure emissions ranged from 5.4 to 73.2 kg CO_2 equivalent. Twenty-one studies (75%) were judged to have a high risk of bias.

Discussion

Current evidence on the environmental impact of GI endoscopy services is fragmented, methodologically inconsistent, and often limited in coverage. Emissions were dominated by patient travel, energy use and procedure-related products. Broader and more standardized environmental assessments are needed to guide the transition to low-carbon, sustainable GI endoscopy.

INTRODUCTION

The healthcare industry is known to have a substantial impact on the environment through its use of resources (such as minerals, metals, fossil fuels and fresh water), waste generation and pollution of air, soil, and water[1]. More specifically, the healthcare sector is responsible for approximately 5% of global greenhouse gas (GHG) emissions, contributing significantly to climate change with serious threats to ecosystems and human health[1].

Gastrointestinal (GI) endoscopy contributes considerably to healthcare-related climate change, primarily due to its resource-intensive decontamination procedures, substantial waste production, high volume of procedures, and reliance on single-use, non-recyclable products[2, 3]. However, the environmental impact, or "environmental footprint", of GI endoscopy remains incompletely quantified.

Environmental impact of healthcare services is commonly assessed using carbon footprinting and Life Cycle Assessment (LCA). Carbon footprinting focuses on Global Warming Potential (GWP), quantifying GHG emissions in carbon dioxide equivalents (CO_2e)[4, 5]. Emissions are typically categorized by the GHG Protocol into scope 1 (direct emissions from facility-controlled sources), scope 2 (indirect emissions from purchased energy), and scope 3 (all other indirect emissions, including supply chains, travel, and waste)[6]. Scope 3 emissions cover over 70% of healthcare-related GHG emissions[7]. An LCA offers a more comprehensive approach, evaluating environmental impact across defined stages of a product's or process's life cycle, which may extend from raw material extraction to its disposal ('cradle-to-grave') in accordance with ISO 14040 and ISO 14044 standards[8]. It involves defining a functional unit, setting system boundaries, and compiling an inventory of inputs and outputs using process-based or financial activity data. Environmental impacts are then quantified and categorized across multiple dimensions such as GHG emissions, ecotoxicity and resource depletion[9]. Results are analyzed in terms of completeness, consistency, sensitivity, and uncertainty. Both LCA's and carbon footprinting are able to identify environmental hotspots and support environmental performance over time.

Recognizing the need for sustainable practices in GI endoscopy, the European Society of Gastrointestinal Endoscopy (ESGE) and the European Society of Gastroenterology Nurses and Associates (ESGENA) issued a position statement in 2022[10]. This statement calls for greater awareness of the environmental footprint of GI endoscopy and provides guidance on reducing its environmental impact. It also emphasizes the necessity of high-quality research to quantify the environmental impact of GI endoscopy and to develop actionable strategies for mitigating its environmental footprint.

Previous reviews of the environmental sustainability of GI endoscopy predominantly focus on carbon emissions, often without comprehensively addressing the broader environmental impact[11-15]. Moreover, these reviews in general lack a systematic methodology and insufficiently appraise the quality of the studies included.

The present systematic review aims to provide a comprehensive overview of the existing literature on the environmental impact of GI endoscopy services. Special attention is given to the carbon footprint of GI endoscopy, with emissions categorized across emission scopes 1, 2, and 3. By synthesizing the available evidence, this review aims to identify key contributors to the environmental footprint of GI endoscopy and key knowledge gaps to inform future research and sustainability efforts in this field.

METHODS

Eligibility criteria and outcomes

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines[16]. The study protocol was registered in the International Prospective Register of Systematic Reviews (PROSPERO, National Institute for Health and Care Research, York, United Kingdom), identification number CRD420250599809. A glossary of terminology used in this systematic review is provided in **Table 1**.

We included peer-reviewed studies assessing the environmental impact of GI endoscopy, with no restrictions on department size or geographical location. Included studies addressed at least one of the sixteen environmental impact categories, as defined by the European Commission[9], or addressed waste, patient or staff travel, or energy consumption. Only studies presenting original data, published in English with full text access were included. Studies comparing endoscopy services with other care pathways were not included.

The primary outcome was the environmental footprint of GI endoscopy departments, categorized according to the European Commission's environmental footprint impact categories. Secondary outcomes included the comparison of GHG emissions across three emissions scopes (scope 1, 2 and 3), with a focus on identifying key environmental hotspots, and identifying opportunities for future environmental impact studies in the field of GI Endoscopy.

Search strategy

A comprehensive literature search was conducted by a professional librarian across MEDLINE, Embase (OVIDSP) and Web of Science databases through November 12, 2024, with an updated search through May 25, 2025. Custom search queries were developed for each database. The following search terms were used: endoscopy, digestive endoscope or digestive tract endoscopy, different types of GI endoscopy procedures, combined with environment, climate change, global warming, GHG, carbon emissions, carbon footprint, pollution, sustainability, fossil fuels, and specific environmental footprint impact categories such as particulate matter, ionizing radiation, ocean acidification, eutrophication, ozone depletion, land use, soil quality, ecotoxicity, water use, resource use or waste disposal. Reference lists of included studies and relevant reviews were screened for additional eligible studies. A detailed list of the search strategy is shown in **Supplementary table 1**.

Study selection

Duplicate records were removed using Endnote (Clarivate Analytics, Philadelphia, United States) and screened using Covidence software (Covidence systematic review software, Veritas Health Innovation, Melbourne, Australia). Two reviewers (BV, DG) independently screened titles and abstracts. Full-text articles were then assessed for inclusion, with disagreements resolved by consensus. Exclusion reasons were documented and are summarized in **Supplementary figure 1**.

Data extraction

Data extraction was performed in duplicate by two reviewers (BV, DG), including extraction of study details, coverage, environmental assessment methods, system boundaries, and environmental outcomes. Environmental impact was quantified as results from one or more environmental impact categories. For

example: the impact category GWP, measured in GHG emissions, was recorded in kilograms (kg) of CO_2e. GHG emissions were further categorized by GHG emission scope. Results beyond GHG emission scope such as energy consumption (kWh) and waste generation (kg) were reported separately. Results from studies reporting on sustainability interventions with two or more data points were reported as a range. Due to methodological heterogeneity, a meta-analysis was not feasible.

Quality assessment

Risk of bias was assessed using the Center for Environmental Evidence Critical Appraisal Tool (CEECAT), version 0.3[17]. The seven CEECAT criteria were prespecified for endoscopy sustainability studies **(Supplementary Table 2)** and independently rated by two reviewers (BV, DG), with discrepancies resolved by consensus. Studies were classified as low, medium, or high risk of bias, with overall risk determined by the highest score. To address methodological variability, the ESGE recently published a position statement outlining minimum criteria for environmental impact assessments in GI endoscopy, including a checklist to guide study design, reporting, and interpretation (E-SPARE)[18]. This checklist was used by two reviewers (BV, CBI) to assess these criteria for all included studies. Additionally, for studies reporting LCA's, a *pro forma* quality assessment scoring system adopted from Drew et al. (2021) was used, based on Weidema's guidelines for critical review of LCAs and operationalized by Kouwenberg et al[19-21]. This scoring system consists of sixteen appraisal criteria covering the four phases of LCA and addresses a range of quality indicators, including internal and external validity, transparency, consistency, and bias. A maximum of 35 points could be allocated. Points were assigned for each study by two reviewers (BV, CBI), and a score out of 35 was calculated to provide an indication of overall study quality. All discrepancies were resolved by consensus.

RESULTS

Study characteristics

A total of 2,939 references were identified through database searches (**Supplementary figure 1**) and one through citation screening. After removal of 1,172 duplicates, 1,768 records underwent title and abstract screening. A total of 132 abstracts appeared relevant, and the full papers of these abstracts were assessed. After application of the inclusion and exclusion criteria, a total of 107 articles were excluded, including 17 studies focusing on direct radiation exposure and 6 on room air quality. A total of 28 studies were included[22-49]. These articles were published between 2008 and 2025 (79% in 2023 or later) and originated from Europe (19 studies), the USA (5 studies), and Australasia (4 studies). The studies were primarily conducted in tertiary centers. One study was conducted during the COVID-19 pandemic[22]. Full study characteristics and results are summarized in **Table 2**.

Study design & methodology

Study characteristics

Of the 28 studies, nine used LCAs[28, 37-42, 44, 45], ten were prospective studies[22-24, 26, 30, 32, 33, 35, 46, 47] with five of them focusing on sustainability interventions[22, 23, 26, 30, 35], seven were retrospective studies[25, 27, 31, 36, 43, 48, 49], and one reported a survey[34]. Twenty-three studies assessed one or more environmental impact categories, with GWP reported in all (**Figure 1**)[22-32, 34, 36-42, 44, 45, 47, 49]. Fresh water use[24, 38, 39, 45, 46] and energy consumption[24, 26, 27, 31, 36, 47] were assessed in five and six studies, respectively. Seven studies covered entire departments[31, 36, 47] or procedures[25, 32, 37, 44], while eleven focused on specific products, including capsule endoscopy[32], endoscopy devices[40, 42], and endoscopes[38, 39, 45].

System boundaries

Twelve studies adopted a “cradle-to-grave" approach, while two used “cradle-to-gate”, meaning the coverage of the life cycle of products only up to the product’s departure from the manufacturing facility (“gate”). The remaining studies focused on travel, electricity consumption and/or waste generation. Of ten relevant GHG Protocol components, two lacked dedicated assessment (**Figure 2**). Scope 3 emissions inclusions were inconsistent, such as patient and staff travel, and manufacturing of medical products and pharmaceuticals (**Supplementary table 3**).

Data sources

Two studies used a hybrid approach combining financial activity and process data[36, 45], while others used a process-based approach. Emission factors were drawn from a range of data sources, including the GHG protocol and national databases. Emissions from electricity consumption were based on the energy mix in each country, with one study noting a 32% reduction in CO2 emissions when switching to 100% renewable energy[31]. An overview of study methods is presented in **Supplementary Table 4**.

Study results

Carbon footprint of entire departments and procedures

Three studies examined the carbon footprint of GI endoscopy departments. Of these, Lacroute et al. reported an annual GHG emission of 241.2 tons CO_2e for 2021, or 28.4 kg CO_2e per procedure, with the largest contributors being patient and staff travel (45%) and medical and non-medical products (32%)[36]. Rughwani et al reported GHG emissions of 3,244 patients undergoing 3,873 procedures in an ambulatory endoscopy clinic in India, showing a total carbon footprint of 148.9 tons CO_2e, or 38.5 kg CO_2e per procedure, of which 83% were emissions from patient travel[47]. Henniger et al. reported 62,720 kg CO_2e annually in a mid-sized department (8,000 to 8,500 procedures per year), equating to 7.8–8.4 kg CO_2e per procedure, excluding patient travel and medical and non-medical products[31].

Four studies investigated the carbon footprint of a specific endoscopic procedure. Elli et al. reported 5.4 kg CO_2e per gastroscopy and 6.7 kg CO_2e per colonoscopy, not including travel of patients or staff, or medical products[25]. Lämmer et al. reported 56.4 kg CO_2e per colonoscopy, including transport of patients and staff, and 14.2 kg CO_2e when excluding transport[37]. Major contributors were transportation of patients and staff (76.5%) and the use of single-use products (13.5%). Another study reported 5.6 kg CO_2e per colonoscopy, emphasizing the significance of patient travel and bowel preparation pharmaceuticals[32]. Colon capsule endoscopy had lower emissions compared to colonoscopy, where patient travel contributed up to 80% in that study. Pioche et al. found even higher numbers for small bowel capsule endoscopy, with patient travel contributing up to 94.7% of total emissions[44].

Scope 1 and 2 emissions

Three studies evaluated scope 1 emissions, with heating-related CO_2 emissions ranging from 2.23 kg CO_2e to 4.8 kg CO_2e per procedure [31, 36, 47]. Scope 2 emissions from energy use were assessed in six studies, with significant variability[24, 26, 27, 31, 36, 47]. Henniger et al. reported zero emissions due to the use of renewable energy while other studies reported electricity-use and related emissions ranging from 0.2-5.5 kWh or 0.1–1.4 kg CO_2e per procedure (**Supplementary Table 5**)[31]. One study reported 19.8 kWh or 7.4 kg CO_2e per procedure[24].

Scope 3 emissions

Ten studies[28, 29, 32, 38-42, 45, 49] quantified the environmental impact of scope 3 emissions of medical products, with reusable endoscopes generally having a much lower footprint per procedure than single-use models. For example, Le et al. concluded that single-use duodenoscopes produced 47 times more GHG emissions per procedure than reusable duodenoscopes[38]. Additionally, endoscopy devices such as biopsy forceps and snares generated considerable emissions, with biopsy-related emissions also being notable[40, 42]. Resecting colonic adenomas by endoscopic submucosal dissection (ESD) generates almost double the amount of GHG compared to piecemeal endoscopic mucosal resection (P-EMR), mostly because ESD is a more complex procedure and therefore generally takes place in expert centers, generating a higher carbon footprint for patient travel[29]. An LCA reported 0.3 kg CO_2e for processing of GI biopsies[28]. Another study showed that using an innovative tool called EndoFaster to analyze gastric juice during upper endoscopy instead of standard biopsy sampling can reduce gastric biopsies by 50% and CO_2 emissions by 44%[49]. Another study describing an LCA of sterile water bottles during colonoscopies concluded that emissions varied mostly per disposal method, totaling 0.2 kg per bottle for landfilling, 0.3 kg for recycling and 0.4 kg for incineration[41]. Travel emissions ranged from 0.1–1.94 kg CO_2e for staff[34, 36, 44] to 6.6–18.4 kg CO_2e for patients[32, 34, 36, 44, 47], with patient travel being a significant contributor to the carbon footprint of departments (up to 45%) or procedures like capsule

endoscopy (up to 95%) (**Supplementary Table 6**). Waste disposal per procedure, quantified in twelve studies[22-24, 30, 33, 35-37, 43, 46-48], ranged from 0.3–3.6 kg, with studies varying in types of waste considered (general waste, infectious waste, recyclables, sharps waste) and disposal methods used (landfill, incineration, recycling) (**Figure 3, Supplementary Table 7**).

Analysis of carbon footprint contributions

Carbon footprint contributions varied significantly across studies. For endoscopy departments, patient and staff travel was the leading contributor, followed by single-use products and energy use. Climate control and room lighting were the primary energy sources. Waste generation played a minor role in overall emissions. For single-use products, manufacturing was the primary contributor, while for reusable products, reprocessing (decontamination) had the most impact.

Study quality and reporting of evidence

A total of 21 (75%) studies[23, 26, 27, 29-35, 39-46, 48, 49] were considered to have a high risk of bias, primarily due to potential confounding factors and measurement bias caused by failure to blind study participants and/or study outcome assessors, or by omitting certain processes from the system boundary, resulting in underreporting of environmental impact. When applying the E-SPARE checklist criteria on reporting of endoscopy sustainability studies to all included studies, we found that 17 studies (61%) adequately reported on most (>50%) criteria. Study objectives, system boundaries and emission factor sources were reported in 20 (71%), 23 (82%), and 21 (75%) studies, respectively. However, 18 studies (64%) did not provide a clear functional unit, and 19 studies (68%) provided no justification for chosen environmental impact assessment methods. Only five studies[25, 30, 31, 34, 47] (18%) reported GHG emissions according to the three emission scopes, and five studies[28, 29, 36, 44, 45] (18%) reported an uncertainty assessment. The quality of the LCA studies, which were additionally assessed using a *pro forma* quality assessment scoring system, ranged from moderate to high (66-84%). However, both internal and external validity were compromised by limited transparency. Three of ten LCA studies [28, 38, 41] conducted sensitivity analyses, revealing significant variability in results (up to 20%). Seven studies lacked clear justification of the functional unit, and nine studies failed to report the significance of exclusions or assumptions. An overview of risk of bias and quality assessment of included studies can be found in **Supplementary Table 2, 8 and 9**.

DISCUSSION

Main findings

This systematic review highlights substantial variability in the estimated carbon emissions per GI endoscopy procedure, ranging from 5.43 kg to 73.2 kg CO_2e. Despite substantial differences in methodology and coverage, three consistent hotspots emerged from included studies: patient travel, energy consumption, and use of single-use products.

With approximately 134 million GI endoscopy procedures performed globally each year[50], extrapolated annual emissions range from 727 million to 9.8 billion kg CO_2e[51]. Travel-related emissions accounted for 45–95% of per-procedure totals, suggesting that integrating telemedicine for pre- and post-procedural consultations, where clinically appropriate, could substantially reduce this burden. In addition, variability in emissions from both patient and staff commuting highlights the potential value of decentralizing services. Locating endoscopy closer to patients' homes, such as through satellite centers or regional hubs, may further reduce travel-related emissions while maintaining access to care. Energy use—particularly in procedure rooms and reprocessing areas—was another major contributor. One study reported a total energy consumption of 19.8 kWh per day, almost 3-fold higher than other studies[24]. This study included energy use in pre-procedure and post-procedure areas, while other studies excluded this from their analysis, possibly explaining this difference[25-27]. Transitioning to renewable energy sources, as demonstrated in selected centers, can potentially reduce energy emissions to near zero[31]. However, implementation must consider the local energy mix and institutional infrastructure. Single-use products were another major contributor. High volumes of single-use biopsy forceps, polypectomy devices, single-use endoscopes and sterile packaging contribute significantly to material use, manufacturing emissions, and waste incineration. While single-use products have three to ten times higher life cycle emissions than reusable products, persistent concerns around infection control and reprocessing capacity continue to drive reliance on single-use products[52, 53]. Although waste generation ranged from 0.5 to 3.5 kg per procedure, it generally contributed to less than 3% of total departmental emissions[36, 47].

Emissions varied with procedure type, use of single-use versus reusable products, institutional waste policies, and local energy sources. Similar variability has been observed in other resource-intensive clinical environments, such as intensive care units and operating rooms[54, 55]. Only four of the twenty-eight studies[37-39, 45] assessed environmental impacts beyond GHG emissions (e.g., water use, ecotoxicity, or resource depletion), and three studies examined the environmental footprint of entire endoscopy departments. Moreover, reporting across the GHG Protocol's three emission scopes was inconsistent. Scope 3 emissions were reported in 22 studies (81%), yet coverage remained incomplete. Potentially important contributors such as pharmaceuticals and chemicals were mostly not included.

Strengths

This review offers a comprehensive synthesis of the environmental impact of GI endoscopy, encompassing a broad range of environmental indicators and methodological approaches. By aligning our analysis with the GHG Protocol, we provide a structured perspective on emissions across procedural and departmental levels. The systematic and transparent review methodology, combined with a critical appraisal of study quality, enhances the rigor and robustness of our findings.

Limitations

Despite growing interest in the environmental sustainability of endoscopy, the current evidence base remains limited. Many studies focused narrowly on specific elements—such as waste, energy use, or individual devices—without accounting for the full procedure or departmental context. Substantial methodological heterogeneity, unclear system boundaries, and limited transparency in data sources hinder comparability. Reported footprints varied depending on data sources and regional assumptions; studies based on fossil-fuel-dominated energy mixes, including full life cycle impacts, or single-use products, generally reported higher emissions than those with narrower boundaries or cleaner energy assumptions. Differences in reprocessing protocols, waste management, and product lifespan add further uncertainty. Comparative studies often overlooked shared resource use, potentially underestimating total environmental impact. Risk of bias was assessed using the CEECAT tool, the only instrument currently targeting sustainability studies. As a 2023 prototype tool without formal validation in healthcare sustainability research, CEECAT raises concerns about construct validity. To address this, we operationalized the criteria for endoscopy sustainability studies, applied dual independent review with consensus, and complemented CEECAT with the ESGE E-SPARE checklist and an LCA appraisal framework to provide a broader assessment of study quality. These limitations highlight a broader methodological gap, as validated tools for assessing study quality in sustainability research are currently lacking.

Implications for practice, policy and future research

Sustainable transformation of GI endoscopy must be informed by high-quality, system-wide assessments. Current research is mostly fragmented, focusing on isolated components such as waste or energy. A life cycle perspective is essential to identify trade-offs—for instance, interventions that reduce waste may inadvertently increase water or energy use.

The recent ESGE position statement on sustainability in endoscopy (E-SPARE) provides an important step toward more standardized and transparent reporting[18]. However, in our systematic review, no study reported on all E-SPARE reporting criteria. Furthermore, harmonization must extend beyond reporting alone. Standardization of assessment methods is essential to improve comparability across studies and support benchmarking of sustainability interventions across institutions and countries. Only through consistent, comprehensive measurement, the field can assess progress and identify effective decarbonization strategies. To improve the quality and comparability of future studies, environmental assessments in GI endoscopy should follow standardized methods such as LCA and the GHG Protocol, in line with ESGE's E-SPARE reporting criteria. Where feasible, studies should account for the full life cycle of products and processes, report impacts per procedure, and transparently document data sources and assumptions. Comprehensive inclusion of scope 1, 2 and 3 emissions—particularly scope 3—is essential. Publishing GI-specific methodological details will further improve reproducibility and support the development of best practices.

Conclusion

Current evidence on the environmental impact of GI Endoscopy services is fragmented, methodologically inconsistent, and often limited in coverage. Emissions are dominated by patient travel, energy use, and procedure-related products, while waste contributes comparatively less. Broader and more standardized environmental assessments are essential to support the transition to low-carbon, sustainable GI endoscopy.

TABLES

Table 1 – Glossary of terminology used in this systematic review

Term	Definition/description
Carbon dioxide equivalent (CO_2e)*	Standardized metric to quantify emissions of various greenhouse gases (GHGs) based up on their global warming potential relative to carbon dioxide (CO_2)
Carbon footprint*	Total set of greenhouse gas emissions generated directly and indirectly by an individual, event, organization or product
Endoscopy device	Products typically used during endoscopy procedures, e.g. biopsy forceps, polypectomy snare, hemostatic clips
Environmental footprint	Method that quantifies how much natural resources are consumed by an individual, event, organization, or product. Can be broken down into multiple impact categories, such as resource depletion, land use, or toxicity[56]
Fossil fuel*	Fuel derived from fossilized hydrocarbon deposits, primarily composed of carbon. Examples include coal, petroleum, and natural gas
Functional unit*	The measure of a product or system determined by the performance it delivers in its intended use (i.e., item or process that is being measured)
Global warming potential (GWP)*	Measure developed to quantify the warming effects of various gases relative to CO_2 emissions. A GWP greater than 1 indicates that a particular gas has a greater warming effect on Earth compared to CO_2 during that specific timeframe (usually 100 years)
Greenhouse gases (GHGs)*	Atmospheric elements that absorb and release radiation at particular wavelengths within the range of terrestrial radiation emitted by the Earth's surface, the atmosphere, and clouds. This characteristic leads to the greenhouse effect. Key GHGs include water vapor, carbon dioxide, nitrous oxide, methane, and ozone
ISO 14040/14044 standards*	International Organization for Standardization (ISO) refers to a worldwide federation of national standards bodies. In this particular case, ISO 14040/14044 refers to international standards that cover life cycle assessment (LCA) studies
Landfill waste*	Landfill waste refers to solid waste materials such as nonrecyclable items (plastic bags, food waste, paper products, and other household waste) that are disposed of in specially designed areas called landfills. Also, in the present context, non-recyclable endoscopy supplies not contaminated with body fluids
LCA*	Life cycle assessment. Methodology that systematically evaluates the environmental factors and potential consequences of product systems through a "cradle-to-grave" or "cradle-to-cradle" analysis, spanning from obtaining raw materials to their ultimate disposal, according to specified objectives and boundaries
LCA goal and scope*	*First phase of an LCA*: Includes the specifying principles (functional unit and system boundaries), requirements and guidelines to assess the environmental impact of products, processes, and organizations
Life cycle inventory (LCI) analysis phase*	*Second phase of an LCA*: Compilation and quantification of data inputs and outputs for a product or service throughout its life cycle, necessary to meet the goals of the defined study

Life cycle impact assessment (LCIA) phase*	*Third phase of an LCA*: Evaluation of the scale and importance of potential environmental impacts associated with a product system over its entire lifecycle. In this phase, LCI results are assigned to impact categories, with specific emissions and resource usages linked to broader environmental and human health impacts. These results provide insights into the environmental concerns linked with both the inputs and outputs of the product system
Life cycle interpretation*	Final phase of an LCA: Summary and discussion of LCI and/or LCIA results in relation to the defined goal and scope, in order to reach conclusions and recommendations
Life cycle model	Model to determine what life cycle stages (raw material extraction, also called 'cradle', manufacturing & processing, transportation, usage & retail, waste disposal, also called the 'grave') are covered in an LCA, structuring the process of data collection and analysis[8]
Cradle-to-gate	Model for assessment of the manufacturing process of a product, covering the product lifecycle from raw material extraction ("cradle") up to the product's departure from the manufacturing facility ("gate")[8]
Cradle-to-grave	Model for comprehensive assessment of the life cycle of a product, from raw material extraction ("cradle") up to its disposal ("grave")[8]
Material	A physical substance that objects (products) can be made from
Product	An article or substance that is manufactured or refined for sale. A product is made of one or more materials
Single-use product	Products that are used once, or for a short period of time before being discarded or recycled
Reusable product	Products that can be used multiple times for its intended purpose or a different purpose, rather than being discarded after a single use
Regulated medical waste*	Nonrecyclable items saturated with body fluids or containing infectious agents
Scopes 1, 2 and 3*	*Scope 1:* Direct emissions (e.g. fuel combustion for boilers or vehicles, CO_2 insufflation) *Scope 2:* Indirect emissions associated with the purchase of electricity (e.g. for heating, ventilation, or cooling) *Scope 3:* Indirect emissions generated within the supply chain of endoscopic supplies (manufacturing, transportation, and disposal)
System boundary*	A defined set of criteria for selecting the unit processes that form a product system

323 ** Definitions adopted from Cunha Neves et al (2025)[18].*

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Table 2 – Study characteristics, methods and outcomes

Study Characteristics			Study methods			Outcomes	
Author (year) [ref] Country	**Assessment period and number of procedures assessed**	**Assessment type**	**Setting**	**System boundaries**	**Environmental impact categories assessed**	**Reported GHG emissions (kg CO_2e)**	**Other reported measures**
Cunha Neves et al. (2023) [22] Portugal	October 2021 - March 2022; Pre-intervention (T0): 185 endoscopies, One month after intervention (T1): 178. Four months after intervention (T2): 172	Sustainability intervention study	Waste generated by GI endoscopy during 4 weeks	Included: landfill waste, Regulated Medical waste, Recycled plastic, Recycled paper Excluded: sharps waste, pre- and post-interventional waste, waste due to endoscope reprocessing	GHG emissions; Waste generation (kg)	RMW: T0: 362.1 (82.5%), T1: 212.1 (70.7%), T2: 204(70.1%) Total carbon footprint: T0: 438.7, T1: 299.9, T2: 286.6	Landfill waste: T0: 76.6kg (38.8%), T1: 87.8kg (51.2%), T2: 82.6kg (50.9%) RMW : T0: 120.7kg (61.2%), T1: 70.7kg (41.2%), T2: 68kg (41.9%). Recycled paper: T0: 0kg (0%), T1: 4.7kg (2.8%), T2: 3.8kg (2.3%). Recycled plastic: T0: 0kg (0%), T1: 8.2kg (4.8%), T2: 8kg (4.9%). Total waste: T0: 197.3kg, T1: 171.4kg, T2: 162.4kg
De Jong et al. (2023) [23] the Netherlands	February 2020; 15 procedures + February 2021: 21 procedures	Sustainability intervention study	Waste generated per endoscopy procedure	GI endoscopy unit with 10,000 procedures per year	GHG emissions; Waste generation (kg)	Baseline measurement (T0): 4.69 per procedure After recycling (T1): 4.55 per procedure	T0: total: 0.97 kg, 85% residual waste, 9.6% recyclable plastic waste. T1: 0.89 kg, 8.9% recyclable plastic waste
Desai et al. (2024) [24] USA	May-June 2022; 450 EGDs/Colonoscopies in 400 patients	Prospective study	Waste generation and energy use for 100 procedures	Included: total waste (Landfill, biohazard, potentially recyclable, sharps) of all devices, PPE, packaging and tubing. Liquid waste generated from endoscope reprocessing. Energy use of endoscopy unit and endoscopy tower, electrocautery machine, monitors	GHG emissions; Water use; Waste generation (kg); Energy consumption (kWh)	Total emissions: 1,501 Landfill waste: 766.5 Energy consumption: 734.58	For 100 procedures: Waste: 303kg, direct landfill waste: 219kg, biohazard: 72.8kg, sharps: 11.1kg, recyclable items: 61kg Endoscope reprocessing: 5,243 liters of water Energy consumption: 1,980kWh
Elli et al. (2024) [25] Italy	Unknown	Retrospective study	One upper or lower GI endoscopy procedure	Included: energy use (including energy required to operate endoscopes, climate, lighting of the endoscopic room, use of computers), Endoscope reprocessing, use of PPE, single use devices and products, vascular access, paper to print report and pictures, histology processing. Excluded: Energy consumption during manufacture and transportation of materials	GHG emissions, energy consumption (kWh)	EGD: 5.43 Colonoscopy: 6.71	Energy consumption EGD: 5.5kWh per procedure Colonoscopy: 11.0kWh per procedure
Fichtl et al. (2024) [26] Germany	Baseline (T0): 30 days + Power saving phase (T1): 30 days	Sustainability intervention study	Energy use per procedure	Included: energy consumption of endoscopy tower	GHG emissions; Energy consumption (kWh)	Center 1: T0: 0.06925, T1: 0.0744, center 2: T0: 0.15928, T1: 0.14428, center 3: T0: 0.15357, T2: 0.14212	Mean power consumption per examination: center 1: T1: 159.56Wh (±23.91), T1: 132.36Wh (±20.51), center 2: T0: 367.01Wh (±40.65), T1: 332.44Wh (±62.6), center 3: T0: 353.84Wh (±93.66), T2: 327.46Wh (±74.51)
Gayam (2020) [27] USA	Unknown	Retrospective study	Energy consumption in a single day	Included: energy consumption of wash machines, endoscopy machines, anesthesia machines, room lighting	GHG emissions; Waste generation (kg); Energy consumption (kWh)	Energy use per year: 15,780	Waste: 1.5 kg of plastic waste (landfill), 0.3 kg recyclable Energy use per day: Wash machines: 24.67 kWh, endoscopy machines: 27.00 kWh, anesthesia machine: 12.00 kWh, room lighting: 47.88 kWh, total: 111.55

							kWh Energy use per year: 29,003 kWh
Gordon et al (2021) **[28]** **USA**	Unknown	Process-based LCA	The processing of one person's biopsy sample	Included: All biopsy materials and supplies used within the laboratory space, associated electricity used, upstream production and downstream treatment or disposal of resources, transportation of staff. Excluded: Manufacturing of capital equipment and buildings, non-electricity energy demand.	GHG emissions	1 specimen jar with biopsies: 0.29, 3 specimen jars with biopsies: 0.79.	N/a
Grau et al (2025) **[29]** **France**	Sep 2019 - Feb 2021, 182 P-EMR, 177 ESD, simulated follow-up period of 18 months	LCA	P-EMR and ESD procedures	Included: Medical devices, bowel preparation, drugs for anesthesia (only packaging), electricity consumption, patient transport Excluded: staff travel, the impact of outpatient clinics, overnight stay in hospital, meals, endoscopes	GHG emissions; Waste generation (kg); energy consumption (kWh)	P-EMR: 63.5 (equipment 10.5, patient transport 32.7, electricity 8.0, anesthesia 12.3), 31.3 excluding transport ESD: 73.2 (equipment 13.3, transportation 33.4, electricity 12.5, anesthesia 12.9), 39.3 without transportation Follow-up colonoscopy at local center: 16.5, follow-up at expert center: 43	Waste per procedure: 1.7 kg for P-EMR, 2.3 kg for ESD Waste for one standard simulated follow-up colonoscopy: 0.6 kg
Henniger et al. (2023) **[30]** **Germany**	1 February 2022 - 1 May 2022 and 1 February 2023 - 1 May 2023 (intervention period); 1,738 + 1,666 endoscopies	Sustainability intervention study	Waste generated per day	Included: consumables (transportation, production, waste burning), waste, energy related emissions	GHG emissions; Waste generation (kg)	Control: 8,010, Intervention: 7,090	Total waste: control: 70.84kg/day, intervention: 69.88kg/day
Henniger et al. (2023) **[31]** **Germany**	1 January 2022 to 31 December 2022; middle-sized GI endoscopy unit (8,000-8,500 procedures)	Retrospective study	All procedures in a GI endoscopy unit for one year	Included: electrical power and gas used for heating, waste treatment, endoscopic devices and protective materials (manufacturing, packaging, transportation: cradle to gate) Excluded: staff travel needs, capital goods	GHG emissions; Waste generation (kg); Energy consumption (kWh)	Total emissions: 62,720 per year. Scope 1: consumption of natural gas: 35,910 Scope 3: 26,810, 14,150 materials, 8,470 extraction, processing and transport of natural gas and electricity, 890 packaging, 2,750 transportation, 550 handling waste	Scope 2 (Electricity): 46,622kWh (from regenerative sources, so CO_2e = 0kg)
Jalayeri Nia et al (2024) **[32]** **UK**	December 2022 - September 2023; 25 patients	Prospective study	Colorectal cancer screening via conventional colonoscopy (P1), home-delivered CCE (P2), or clinical CCE (P3)	P1: patient travel, energy usage and waste disposal, polyp removal, IM morphine used as proxy for sedation and analgesia medicines P2: patient travel P3: courier service delivering and collecting the smartbox, staff travel Excluded: Colonoscopy capsules, 5G hardware and smartbox manufacture, bowel preparation	GHG emissions	P1: Base case (BC): travel 6.62, Procedure 5.46, Pharma 0.02, total 12.10 Optimised case(OC): Travel 2.52, Procedure 3.06, Pharma 0.02, Total 5.60 P2: BC: travel 17.09, Procedure 3.87, Pharma 0.01, total 20.98 OC: Travel 7.99, Procedure 1.56, Pharma 0.01, Total 9.57 P3: BC: travel 12.67, Procedure 3.87, Pharma 0.01, total 16.56 OC: Travel 1.36, Procedure 1.56,	N/a

						Pharma 0.01, Total 2.94	
Jung et al (2025) [33] South Korea	October 2023, 3,922 endoscopies in 7 hospitals	Prospective study	Waste of GI endoscopy procedures in South Korea	Excluded: Specific therapeutic interventions, such as endoscopic resection and stent insertion	Waste generation (kg)	N/a	Total waste: 4,558 kg Mean weight per procedure: 1.34kg Disposable weight per EGD: 0.24 kg (0.05-0.35 kg) Disposable waste per colonoscopy: 0.43 kg (0.12-0.61 kg)
Klose et al (2024) [34] Germany	January to June 2023; 300 procedures in 260 patients	Survey	One outpatient endoscopy procedure	Included: travel for pre-endoscopic consultation and the endoscopic procedure	GHG emissions	Patients: 10.7 Staff: 0.8	N/a
Kojima et al (2008) [35] Japan	November 2004 - November 2005; 220 panendoscopies, 87 colonoscopies	Sustainability intervention study	n/a	Included waste categories: sharp infectious waste, needle, infectious waste, non-infectious waste, non-infectious plastic waste	Waste generation (kg)	N/a	Before HACCP implementation: Sharp infectious waste: 6.6kg (7.1%), Infectious waste: 86.6kg (92.9%), Total: 93.2kg After HACCP implementation: Sharp infectious waste: 6.4kg (6.8%), Needle: 0.2%, Infectious waste: 64.2kg (68.9%), Non-infectious waste: 17.7kg (19.0%), Non-infectious plastic waste: 4.611kg (4.9%), Total: 93.2kg
Lacroute et al (2023) [36] France	January 2021 to December 2021; 8524 procedures for 6070 patients	Retrospective study	One endoscopy procedure	Included: Energy use, medical gases, medical and non-medical equipment, consumables including, food products, laundry services and cleaning, patient and staff travel, waste Excluded: manufacturing of products not in database, transportation of products from outside Europe	GHG emissions; Waste generation (kg); Energy consumption (kWh)	Total emissions: 241,400 (+/- 56,000). Per procedure: 28.4 Travel: 110,014 (45%), medical and non-medical equipment: 77,556 (32%), energy: 28,937 (12%), electricity: 3,000, Consumables: 17,339 (7%), Waste: 6,639 (3%), Freight: 619t (0.4%), Medical gases: 1.1 (0.005%)	Electricity: 57,840 kWh Waste: 1.5kg per procedure
Lämmer et al (2025) [37] the Netherlands	July 17-27, 2023; 13 colonoscopies	Process-based LCA	Diagnostic colonoscopy procedures	Included: Extraction of raw materials, production, transport, use phase, waste processing, reprocessing, energy and water use. Excluded: Hospital infrastructure and medical gas infrastructure	GHG emissions; Waste generation (kg); Energy consumption (kWh); raw material extraction; water use; human carcinogenic toxicity, human health	56.4 per colonoscopy Excluding transport: 14.2 per colonoscopy	Human health damage: $11.3 \cdot 10^{-5}$ DALYs per colonoscopy, 137 L water consumed Transportation of patients/staff: 76.5% of total, disposables: 13.5%
Le et al (2022) [38] USA	Unknown	Process-based LCA	One ERCP using one of three duodenoscopes: conventional RD, RD with disposable endocaps, SD	included: manufacturing, transportation and packaging, disposal, cleaning, infection treatment, and electricity during use Excluded: recycling of SD's	GHG emissions; Acidification; Eutrophication; Resource depletion; Ionizing radiation; Ozone depletion; Water use; Ecotoxicity; Land use; Waste generation (kg); Human health	Performing an ERCP with an SD: 36.3 - 71.5 (91-96% manufacturing, 3-5% disposal) RD: 1.53 (electricity use 62%, cleaning and disinfection 26%) RD with disposable endcap: 1.54	Human health (DALY): DALY for RD: 2.31E-04, RD with disposable endcap : 1.15E-04 Other outcomes (end-point): RD: Human health DALY (DALY): 1.31E-05, Ecosystem quality species per year (EQSy): 6.22E-08, Resource consumption USD2013 (RCusd): 8.50E-02 RD with disposable endcaps: DALY: 1.29E-05, EQSy: 6.12E-08, RCusd: 8.53E-02 SD (lower bound): DALY: 1.70E-04, EQSy: 2.58E-07, RCusd: 2.24E+00

							SD (upper bound): DALY: 3.42E-04, EQSy: 4.67E-07, RCusd: 4.28E+00
López-Muñoz et al (2024) [40] Spain	16,000 RD, 1,600 SD procedures and a combination of 1,405 uses of an RD plus 195 procedures using SDs	Process-based LCA	One ERCP procedure	Excluded: electricity consumption during ERCP, medical and non-medical equipment, other consumables, general waste, travel	GHG emissions; Acidification; Ionizing radiation; Water use; Resource depletion	Emissions per one endoscopy: RD: 0.1, SD-A: 7.9, SD-B: 6.6 Emissions for one endoscopy when endoscope is used 1,600x: RD: 152 SD-A: 12,640, SD-B: 10,512 Reusable + single use A (1,405x RD plus 195x SDs): 1,677 Reusable and single use B (1,405x RD plus 195x SDs): 1,417	RD: Acidification (Ac): 0.16 mol H+ eq, Water use (WU): 7.17m3, Resource use (RU): 0.00116kg Sb-eq, Ionizing radiation (IR): 0.95kg 235U-eq SD-A: Ac: 0.02 mol H+ eq, WU: 1.31m3, RU: 0.00012kg Sb-eq, IR: 0.15kg 235U-eq SD-B: Ac: 0.011mol H+ eq, WU: 0.91m3, RU: 0.00012kg Sb-eq, IR: 0.15kg 235U-eq
López-Muñoz et al (2023) [39] Spain	June 2022 to July 2022; 143 devices: 75 biopsy forceps, 49 polypectomy snares and 19 haemostatic clips, to assess the efficacy of a "green mark"	Process-based LCA + one-week prospective sustainability intervention study	Devices from four manufacturers (A, B, C and D): biopsy forceps (A, B and C), polypectomy snares (A, B and D), haemostatic clips (A and B)	Included: Extraction of material and energy resources, manufacturing, transport of production process and disposal, weight and composition of endoscopy devices Excluded: manufacturing and assembly steps (injection, extrusion and lamination) were not included (around 15% of total)	GHG emissions	Haemostatic clips: 0.49 (range 0.41-0.57) Snares: 0.41 (range 0.38-0.44) Forceps: 0.41 (range 0.31-0.47) Total: 67.74 After intervention: -18.26 (-27.44%)	N/a
Lotter et al (2025) [41] Australia	77,342 sterile water bottles	Process-based LCA	Sterile water bottles used for colonoscopy	Included: sterile water bottles manufacturing, transport and disposal Excluded: transport of waste, oil used to produce bottles, transport of bottles in the region	GHG emissions	Total 77,342 bottles: landfill 15,247, recycling 23,035, incineration 31,330 Per bottle: landfill 0,197, recycling 0,298, incineration 0,405	N/a
Martin-Cabazuelo et al (2024) [42] Spain		Process-based LCA	Snares (S1-3), hemoclips (H1, H2), biopsy forceps (F1-3)	Included: production, assembly, transportation, waste management Excluded: sterilization, user manuals	GHG emissions	S1 0.72, S3 0.52 F1 0.69, F3 0.48 H1 0,54, H2 0.80	N/a
Namburar et al (2022) [43] USA	5-day audit in January and February 2020; 278 endoscopies for 243 patients	Retrospective study	One endoscopy procedure	Included: pre- and post-procedure care Excluded: waste from patient waiting areas, staff break rooms and sharps waste	Waste generation (kg)	N/a	Total: All: 619kg, low volume centre (LVC): 73kg, high volume centre (HVC): 546kg Per endoscopy: All: 2.11kg, LVC: 1.96kg, HVC: 2.27kg Landfill: All: 1.34kg (64%), LVC: 1.33kg (68%), HVC: 1.36kg (60%) Biohazard: All: 0.59kg (28%), LVC: 0.64kg (32%), HVC: 0.54 kg (24%) Recycled: All: 0.18kg (9%), LVC --> 0kg (0%), HVC: 36kg (16%) Reprocessing: All: 0.30kg, LVC: N/A, HVC 0.33kg
Pioche et al (2023) [44] France	November 2022 - February 2024; 100 patients, Three devices: PillCam (PC), CapsoCam (CC), NaviCam (NC)	Process-based LCA; survey	One small bowel capsule endoscopy procedure	Included: materials, packaging manufacturing, transport, use, disposal, bowel preparation, patient and staff transport, data storage, capsule retrieval Excluded: water to flush toilet, capsule journey	GHG emissions	PC: 19.4, CC: 20.6, NC: 19.5 Including consultations: PC: 27.2 CC: 28.4, NC: 27.3 All packaging components recycled: PC: -0.09, NC: -0.13, NC: -0.06	N/a
Pioche et al	April 2023 to February	Hybrid LCA	The provision of	Included: Manufacture, distribution, usage,	GHG emissions;	SG: total: 10.9, component	SG: depletion fossil resources (DFR): 130

(2024) [45] France	2024		an endoscope for one upper GI endoscopy	reprocessing and disposal of endoscope Excluded: pre- and post-care, patient and staff travel, sedation, bite block, lighting and energy, additional devices (e.g. forceps)	Acidification; Eutrophication; Resource depletion; Water use; Ecotoxicity	production: 5.7, assembly and sterilization: 1.4, supply manufacturer: 0.2 Supply distributor: 0.1 packaging: 1.5, end of life treatment: 2.1 RG: total: 4.7, endoscope production and assembly: 0.02, primary packaging: 0.4, supply: 0.05, decontamination: 2.1, sent for repair: 0.06, sampling: 0.01, end of life treatment: 2.1	MJ, freshwater ecotoxicity (FE): 15.9 kg 1,4-DB_e, terrestrial acidification (TA): 0.12 kg SO_2e, eutrophication (Eu): 0.02 kg PO_4^{3-}e, water consumption (WC): 6.2 M^3 RG: total: DFR: 60.9, FE: 2.6, TA: 0.02, Eu: 0.005, WC: 9.5
Ribeiro et al (2024) [46] Portugal	14-18 February 2022	Prospective study	Waste generated during one endoscopy procedure	Included: the mass of waste from pre and postprocedural areas, endoscopy rooms, as well as the reprocessing area + the amount of water used during the reprocessing of a single endoscope	Water use; Waste generation (kg)	n/a	Total waste = 443.2 kg Endoscopy rooms: 310.8 kg (70%), pre- and postprocedural area: 55.2 kg (13%), reprocessing: 77.2 kg (17%) Waste per procedure: 1.8 kg, of which 1.4kg hazardous (group III) Water consumption: 250 ml for precleaning, 30L for manual cleaning and rinsing (15L for each), 25L high-level disinfection Total (241 procedures): 13,315.3L of water (55.3L per endoscope)
Rughwani et al (2025) [47] India	29 May to 10 June 2023, 3873 procedures in 3244 patients	Prospective study	GI Endoscopy department	Included: Electricity use, water use (reprocessing and laundry), waste, patient travel, medical gas, transport of endoscopes and devices, detergents and disinfectants, laundry Excluded: manufacturing of consumables, endoscopes and medical gases	GHG emissions; Waste generation (kg); Electricity (kWh), water use	Total emissions: 148947.32 or 38.45 per procedure. Patient travel 83.09%, electricity consumption 10.42%, medical gas transport and usage 3.63%, water consumption 1.86%	Waste: total 1,952.50 kg, per procedure 0.504 kg Electricity: total 19,160.4 kWh, per procedure 4.94 kWh Water use: 67.85l per procedure
Vaccari et al (2018) [48] Italy	2013 and 2014 (2 years)	Retrospective study	Hospital waste	Included: non-hazardous healthcare waste including unsorted municipal waste, organic waste and paper/cardboard	Waste generation (kg)	N/a	Total: 0.50kg/procedure Hazardous waste: 3.09kg/day/bed
Zullo et al (2023) [49] Italy	2000 hypothetical upper endoscopy procedures	Retrospective study	Upper GI biopsy sampling for one patient	Included: bottles for calibration plus a liquid-draining system, cardboard box for the 3 bottles, washing solution tank, gastric juice suction tube, histology assessment, biopsy forceps, biopsy jar Excluded: calibration liquids and reagents	GHG emissions	Standard biopsy sampling: 1262 per year. EndoFaster: 704 per year	N/a

Please refer to main text for details on references.

CCE, colon capsule endoscopy; CO_2e, carbon dioxide equivalent; DALY, disability-adjusted life years; EGD, esophagogastroduodenoscopy; ERCP, endoscopic retrograde cholangiopancreatography; ESD, endoscopic submucosal dissection; GHG, greenhouse gas; GI, gastrointestinal; HACCP, hazard analysis and critical control points; IM, intramuscular; kg, kilogram; kWh, kilowatt-hour; L, liter; LCA, life cycle assessment; M, meter; MJ, megajoule; n/a, not applicable; P-EMR: piecemeal endoscopic mucosal resection; PO_4^{3-} e, phosphate; PPE, personal protective equipment; RD, reusable duodenoscope; RG, reusable gastroscope; RMW, regulated medical waste; SD, single-use duodenoscope; SG, single-use gastroscope; SO_2e, sulfur dioxide; USA, United States of America; USD, United States dollars; UK, United Kingdom.

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TABLE/FIGURE LEGEND

Table/figure	Title	Caption
Table 1	Glossary of terminology used in this systematic review	* Definitions adopted from Cunha Neves et al (2025)[18].
Table 2	Study characteristics, methods and outcomes	Please refer to main text for details on references. CCE, colon capsule endoscopy; CO_2e, carbon dioxide equivalent; DALY, disability-adjusted life years; EGD, esophagogastroduodenoscopy; ERCP, endoscopic retrograde cholangiopancreatography; ESD, endoscopic submucosal dissection; GHG, greenhouse gas; GI, gastrointestinal; HACCP, hazard analysis and critical control points; IM, intramuscular; kg, kilogram; kWh, kilowatt-hour; L, liter; LCA, life cycle assessment; M, meter; MJ, megajoule; n/a, not applicable; P-EMR: piecemeal endoscopic mucosal resection; PO_4^{3-} e, phosphate; PPE, personal protective equipment; RD, reusable duodenoscope; RG, reusable gastroscope; RMW, regulated medical waste; SD, single-use duodenoscope; SG, single-use gastroscope; SO_2e, sulfur dioxide; USA, United States of America; USD, United States dollars; UK, United Kingdom.
Figure 1	Environmental impact categories assessed in included studies	Presented as percentages of total included studies (n=28)
Figure 2	Distribution of included studies across GHG protocol scopes	Studies across GHG Protocol scopes 1-3 in GI endoscopy, mapped by procedural stage and departmental level. GI, gastrointestinal; GHG, greenhouse gas; n, number; nd, no data.
Figure 3	Types of waste and their percentage per waste category	Categorized using the World Health Organization (WHO) standard healthcare waste categories, excluding pathological, chemical and pharmaceutical waste, as no study examined these categories.

Table S1 – Search Strategy

Database searched	Platform	Years of coverage	Search strategy
Medline ALL	Ovid	1946 - Present	(Endoscopy / OR Endoscopes / OR exp Endoscopy, Digestive System / OR (endoscop* OR colonoscop* OR gastroscop* OR esophagoscop* OR esophagogastroduodenoscop* OR gastroduodenoscop* OR esophagogastroscop* OR eosophagoscop* OR duodenoscop* OR sigmoidoscop*).ab,ti,kw.) AND (* Environment OR Medical Waste Disposal / OR Climate Change/ OR Carbon Footprint/ OR Particulate Matter/ OR Radiation, Ionizing/ OR Ocean Acidification/ OR Eutrophication/ OR Fossil Fuels/ OR (((environment* OR carbon OR co2 OR co-2 OR climate*) ADJ3 (impact* OR sustain* OR footprint* OR emission* OR reduct* OR cost OR pollut*)) OR (greenhouse ADJ (effect* OR gas*)) OR waterlog* OR water-log* OR ((climat* OR global) ADJ (warming OR change OR action*)) OR (waste* ADJ3 (disposal*)) OR green*-endoscop* OR (ozone* ADJ3 (deplet* OR formation*)) OR (human ADJ3 toxicit*) OR particulate-matter* OR PM10 OR PM2-5 OR PM-10 OR PM-2-5 OR ((ionizing OR ionising) ADJ3 radiat*) OR acidificat* OR eutrophicat* OR ecotoxic* OR ecologic*-toxic* OR land-use OR land-transformation* OR (water ADJ3 (footprint* OR consumption* OR deprevat*)) OR water-use OR resource-use OR (resource* ADJ3 depletion*) OR fossil-fuel* OR soil-qualit*).ab,ti,kw. OR (sustainab* OR footprint* OR foot-print* OR environmental* OR climate* OR (green* ADJ2 endoscop*) OR ozone* OR greenhouse OR pollut*).ti.) NOT (* Indocyanine Green / OR (greenlight* OR green-light* OR indocyanine-green*).ti.) NOT (exp animals/ NOT humans/) AND english.la
Embase	Embase.com	1971 - Present	(endoscopy/de OR endoscope/de OR 'digestive endoscope'/exp OR 'digestive tract endoscopy'/exp OR (endoscop* OR colonoscop* OR gastroscop* OR esophagoscop* OR esophagogastroduodenoscop* OR gastroduodenoscop* OR esophagogastroscop* OR eosophagoscop* OR duodenoscop* OR sigmoidoscop*):Ab,ti,kw) AND ('environmental impact'/exp OR 'environmental sustainability'/de OR 'waste disposal'/de OR 'climate change'/exp OR 'carbon footprint'/de OR 'carbon dioxide emission'/de OR 'particulate matter'/exp OR 'ionizing radiation'/de OR acidification/de OR eutrophication/de OR ecotoxicity/de OR 'land use'/de OR 'water footprint'/de OR 'resource use efficiency'/de OR 'resource depletion'/de OR 'fossil fuel'/de OR 'soil quality'/de OR (((environment* OR carbon OR co2 OR co-2 OR climate*) NEAR/3 (impact* OR sustain* OR footprint* OR emission* OR reduct* OR cost OR pollut*)) OR (greenhouse NEXT/1 (effect* OR gas*)) OR waterlog* OR water-log* OR ((climat* OR global) NEXT/1 (warming OR change OR action*)) OR (waste* NEAR/3 (disposal*)) OR green*-endoscop* OR (ozone* NEAR/3 (deplet* OR formation*)) OR (human NEAR/3 toxicit*) OR particulate-matter* OR PM10 OR PM2-5 OR PM-10 OR PM-2-5 OR ((ionizing OR ionising) NEAR/3 radiat*) OR acidificat* OR eutrophicat* OR ecotoxic* OR ecologic*-toxic* OR land-use OR land-transformation* OR (water nEAR/3 (footprint* OR consumption* OR deprevat*)) OR water-use OR resource-use OR (resource* NEAR/3 depletion*) OR fossil-fuel* OR soil-qualit*):Ab,ti,kw OR (sustainab* OR footprint* OR foot-print* OR environmental* OR climate* OR (green* NEXT/2 endoscop*) OR ozone* OR greenhouse OR pollut*):ti) NOT ('indocyanine green'/mj OR (greenlight* OR green-light* OR indocyanine-green*):ti) NOT ([animals]/lim NOT [humans]/lim) NOT ([conference abstract]/lim AND [2000-2022]/py) AND [english]/lim
Web of Science Core Collection	Web of Knowledge	1975 - Present	TS=((endoscop* OR colonoscop* OR gastroscop* OR esophagoscop* OR esophagogastroduodenoscop* OR gastroduodenoscop* OR esophagogastroscop* OR eosophagoscop* OR duodenoscop* OR sigmoidoscop*)) AND (TS=(((environment* OR carbon OR co2 OR co-2 OR climate*) NEAR/2 (impact* OR sustain* OR footprint* OR emission* OR reduct* OR cost OR pollut*)) OR (greenhouse NEAR/1 (effect* OR gas*)) OR waterlog* OR water-log* OR ((climat* OR global) NEAR/1 (warming OR change OR action*)) OR (waste* NEAR/2 (disposal*)) OR green*-endoscop* OR (ozone* NEAR/2 (deplet* OR formation*)) OR (human NEAR/2 toxicit*) OR particulate-matter* OR PM10 OR PM2-5 OR PM-10 OR PM-2-5 OR ((ionizing OR ionising) NEAR/2 radiat*) OR acidificat* OR eutrophicat* OR ecotoxic* OR ecologic*-toxic* OR land-use OR land-transformation* OR (water nEAR/2 (footprint* OR consumption* OR deprevat*)) OR water-use OR resource-use OR (resource* NEAR/2 depletion*) OR fossil-fuel* OR soil-qualit*) OR TI=(sustainab* OR footprint* OR foot-print* OR environmental* OR climate* OR (green* NEAR/2 endoscop*) OR ozone* OR greenhouse OR pollut*)) NOT TI=((greenlight* OR green-light* OR indocyanine-green*)) AND DT=(article) AND LA=(english)

**Science Citation Index Expanded (1975-present) ; Social Sciences Citation Index (1975-present) ; Arts & Humanities Citation Index (1975-present) ; Conference Proceedings Citation Index- Science (1990-present) ; Conference Proceedings Citation Index- Social Science & Humanities (1990-present) ; Emerging Sources Citation Index (2005-present) No other database limits were used than those specified in the search strategies.*

Table S2 – Inventory Boundaries

	Pre-procedure					Procedure						Post-procedure					
Author, (year) [ref] Country	**Patient travel**	**Staff travel**	**Bowel preparation**	**Vascular access**	**Waste**	**Energy use**	**Consumables**	**Capital equipment**	**Endoscope**	**Pharmaceuticals & medical gases**	**Waste**	**Food**	**Laundry**	**Histology**	**Energy use**	**Reprocessing of endoscope**	**Waste**
Cunha Neves et al. (2023) [21] Portugal					X						X						X
De Jong et al. (2023)[22] Netherlands											X						
Desai et al. (2024) [23] USA					X	X					X					X	X
Elli et al. (2024) [24] Italy				X		X	X	X						X*	X		
Fichtl et al. (2024) [25] Germany						X											
Gayam (2020) [26] USA						X									X		
Gordon et al. (2021) [27] USA		X												X			
Grau et al. (2025) [28] France	X		X			X	X			X							
Henniger et al. (2023) [29] Germany					X	X	X				X				X		X
Henniger et al. (2023) [30] Germany							X				X						
Jalayeri Nia et al. (2024) [31] UK	X				X*	X*				X	X*						X*
Jung et al. (2025) [32] South Korea					X						X						X
Klose et al. (2024) [33] Germany	X	X															
Kojima et al. (2008) [34] Japan					X						X						X
Lacroute et al. (2023) [35] France	X	X		X	X	X	X	X	X	X	X	X	X		X	X	X
Lämmer et al. (2025) [36] Netherlands	X	X			X	X	X		X		X		X		X	X	X
Le et al. (2022) [37] USA						X			X							X	
López-Muñoz et al. (2024) [38] Spain									X							X	
López-Muñoz et al. (2023) [39] Spain							X										
Lotter et al. (2025) [40] Australia							X										
Martin-Cabazuelo et al. (2024) [41] Spain							X										
Namburar et al. (2022) [42] USA					X						X						X
Pioche et al. (2023) [43] France			X				X										X
Pioche et al. (2024) [44] France	X	X							X							X	

Ribeiro et al. (2024) [45] Portugal					x						x					x
Rughwani et al. (2025) [46] India	x			x	x	x	x	x	x	x	x		x		x	x	x
Vaccari et al. (2018) [47] Italy					x						x						x
Zullo et al. (2023) [48] Italy							x*							x*			

** = data used from previously published article*

Table S3 – Study Methods

Author, (year) [ref] Country	Data sources	Software used for impact assessment	Characterization method	Allocation method
Cunha Neves et al. (2023) [21] Portugal	Data collection: on site	N/a	Unknown	N/a
De Jong et al. (2023) [22] Netherlands	Data collection: on site	N/a	UK Government GHG Conversion Factors for Company Reporting (2016)	N/a
Desai et al. (2024) [23] USA	Data collection: on site	N/a	US EPA GHGe calculator	N/a
Elli et al. (2024) [24] Italy	Data collection: on site, manufacturers. Secondary data source: scientific literature (Gordon et al[27]). LCI database: Italian Higher Institute for Environmental Protection and Research (2022), emission factors report of the International Energy Agency.	Unknown	US EPA GHGe calculator	Unknown
Fichtl et al. (2024) [25] Germany	Data collection: on site.	N/a	German electricity generation average	N/a
Gayam (2020) [26] USA	Data collection: on site	N/a	Unknown	N/a
Gordon et al. (2021) [27] USA	Data collection: on site. LCI database: EcoInvent database, chemical life cycle collaborative	SimaPro software v8.5.2.3	TRACI (EPA), CLiCC LCIA Estimate tool	APOS (attributional)
Grau et al. (2025) [28] France	Data collection: on site, material composition analysis. Secondary data source: scientific literature. LCI database: EcoInvent v3.8, emission factors reported by ADEME	Granta Design	ADEME	Unknown
Henniger et al. (2023) [29] Germany	Data collection: on site. LCI database: EcoInvent 3.8	Unknown	UK Government GHG Conversion Factors for Company Reporting (2022, v2.0).	Unknown
Henniger et al. (2023) [30] Germany	Data collection: on site. LCI database: EcoInvent v3.8	Unknown	UK Government GHG Conversion Factors for Company Reporting.	Unknown
Jalayeri Nia et	Data collection: on site.	Unknown	Conversion factors from	Unknown

al. (2024) [31] UK			the Department for Energy Security and Net Zero (UK)	
Jung et al. (2025) [32] South Korea	Data collection: on site, manufacturers. Secondary data source: scientific literature (Gordon et al[27]). LCI database: Italian Higher Institute for Environmental Protection and Research (2022)	N/a	N/a	N/a
Klose et al. (2024) [33] Germany	Data collection: on site	N/a	GHG protocol conversion factors (2023)	N/a
Kojima et al. (2008) [34] Japan	Data collection: on site	N/a	N/a	N/a
Lacroute et al. (2023) [35] France	Data collection: on site. Secondary data source: monetary ratios. LCI database: EcoInvent, AGRIBALYSE	Bilan Carbon tool v8.7.1	ADEME Carbon base, Guide sectorial BEGES Sante	Unknown
Lämmer et al. (2025) [36] Netherlands	Data collection: on site. Secondary data source: manufacturers. LCI database: EcoInvent 3.9	SimaPro software v9	ReCiPe 2016	Unknown
Le et al. (2022) [37] USA	Data collection: on site. Secondary data source: manufacturers, cystoscope (Davis et al). LCI database: EcoInvent 3.8	SimaPro software v9.1.1, Epi Suite 4.11.	ReCiPe 2016, USEtox 2.12	Unknown
López-Muñoz et al. (2024) [38] Spain	Data collection: on site, MCA. Secondary data source: EcoInvent, Agribalyse, EF secondary data. LCI database: UK Government GHG Conversion Factors for Company Reporting.	OpenLCA v2.0.3	EF v3.0	Unknown
López-Muñoz et al. (2023) [39] Spain	Data collection: on site, MCA. Secondary data source: scientific literature. LCI database: EcoInvent v3.8.1	OpenLCA v1.11	EF v3.0	Attributional analysis
Lotter et al. (2025) [40] Australia	Data collection: on site	Unknown	Unknown	N/a
Martin-Cabazuelo et al. (2024) [41] Spain	Data collection: on site, MCA. Secondary data source: scientific literature, assumption. LCI database: EcoInvent v3.8.1.	OpenLCA v1.11	EF v3.0	Unknown
Namburar et al. (2022) [42] USA	Data collection: on site.	N/a	N/a	N/a
Pioche et al. (2023) [43] France	Data collection: on site, MCA, manufacturers. Secondary data source: scientific literature. LCI database: CES EduPack 2022	Ansys Granta Edupack software	ADEME	Unknown
Pioche et al. (2024) [44] France	Data collection: on site, MCA. Secondary data source: scientific literature, monetary ratio, assumption. LCI database: EcoInvent v3.8.1, ADEME	SimaPro software v9.3	CML-IA baseline v3.07	Unknown
Ribeiro et al. (2024) [45] Portugal	Data collection: on site.	N/a	N/a	N/a
Rughwani et al. (2025) [46] India	Data collection: on site, manufacturers. LCI database: separate Emission Factors used	Excel, Microsoft	N/a	Unknown

Vaccari et al. (2018) [47] Italy	Data collection: Italian Hospital	N/a	N/a	N/a
Zullo et al. (2023) [48] Italy	Data collection: on site. Secondary data source: biopsy processing data from Gordon et al. [27]	Unknown	Institute for Sustainability Leadership of the University of Cambridge, IPCC	Unknown

ADEME, agence de la transition écologique; APOS, allocation at the point of substitution; BEGES, bilan d'émissions de gaz à effet de serre; CLiCC, chemical life cycle collaborative; CML-IA, institute for environmental sciences impact assessment; EF, environmental footprint; EPA, environmental protection agency; GHG, greenhouse gas; IPCC, Intergovernmental Panel on Climate Change; LCI, life cycle inventory; LCIA, life cycle impact assessment; MCA, material composition analysis; n/a, not applicable; TRACI, tool for the reduction and assessment of chemical and other environmental impacts; USA, United States of America; UK, United Kingdom

Table S4 – Energy use in the endoscopy department

Study	Desai et al. (2024) [23]	Elli et al. (2024) [24]	Fichtl et al. (2024) [25]	Gayam et al. (2020) [26]	Rughwani et al. (2025) [46]
Country	USA	Italy	Germany	USA	India
Endoscopy machine [kWh]		0.7	0.2-0.4	0.7*	
Monitors & computers [kWh]		0.2			
Anesthesia machine [kWh]		0.3		0.3*	
Room lighting [kWh]		1.2		1.2*	
Climate control [kWh]		2.5			
Reprocessing wash machines [kWh]		0.6		0.6*	
Entire department [kWh/day]	**277.1**			**111.6**	
Overall energy consumption per procedure [kWh]	**19.8****	**5.5**	**0.2-0.4**	**2.8***	**4.0**

kWh, kilowatt Hour; USA, United States of America

** Data not directly provided by article, calculations based on their provided average of 40 endoscopies per day.*

*** Data not directly provided by article, calculation based on their provided average for 100 procedures.*

Table S5 – Patient and staff travel emissions in gastrointestinal endoscopy

Study	**Jalayeri Nia et al. (2024) [31]**	**Klose et al. (2024) [33]**	**Lacroute et al. (2023) [35]**	**Pioche et al. (2023) [43]**	**Rughwani et al. (2025) [46]**
Country	UK	Germany	France	France	India
Scope	CCE	Outpatient procedures	Outpatient procedures	SBCE	Outpatient procedures
Patient travel CO_2e/procedure [kg]	6.62-17.09	10.7	15.4	18.4	31.95
Staff travel CO_2e /procedure [kg]	n/a	0.8	1.94	0.1	n/a

CCE, colon capsule endoscopy; CO_2e, carbon dioxide equivalent; n/a, not assessed; kg, kilogram, SBCE, small-bowel capsule endoscopy; UK, United Kingdom

Table S6 – Waste generation in the endoscopy department

Mean waste and waste components							
Author (year) [ref.]	**Country**	**Amount of procedures**	**Infectious waste (%)**	**Sharps waste (%)**	**General waste (%)**	**Recyclables (%)**	**Waste, mean (kg/procedure)**
Kojima et al. (2018) [34]	**Japan**	307	68.9-92.9	0-7.1	0-19.0	0-4.9	**0.30**
Vaccari et al. (2018) [47]	**Italy**	Unknown					**0.50 3.09/bed**
Namburar et al. (2022) [42]	**USA**	278	28		64	9	**2.26-2.27**
Cunha Neves et al. (2023) [21]	**Portugal**	535	41.2-61.2		38.8-50.9	0-7.2	**0.5-1.0**
De Jong et al. (2023) [22]	**Netherlands**	36			85-91.1	8.9-9.6	**0.89-0.97**
Lacroute et al. (2023) [35]	**France**	8,524					**1.5**
Henniger et al. (2023) [30]	**Germany**	1,666			93.7	6.3	**3.6**
Ribeiro et al. (2024) [46]	**Portugal**	241	74.1	0.9	7.2	17.8	**1.8**
Desai et al. (2024) [23]	**USA**	450	24	4	57.6	14.4	**3.03**
Rughwani et al. (2025) [46]	**India**	3,873	64.8	1.1	21.8	12.2	**0.50**
Jung et al. (2025) [32]	**South Korea**	3,922					**1.34**

Categorized using the World Health Organization (WHO) standard healthcare waste categories, excluding pathological, chemical and pharmaceutical waste, as no study examined these categories. Kg, kilogram; ref., reference; USA, United States of America.

Table S7 – Risk of bias assessment for included studies using Collaboration for Environmental Evidence Critical Appraisal Tool (CEECAT)

Author (year) [ref] Country	Criterion 1: Risk of Confounding biases	Criterion 2: Risk of post-intervention /exposure selection biases	Criterion 3: Risk of misclassified comparison biases	Criterion 4: Risk of performance biases	Criterion 5: Risk of detection biases	Criterion 6: Risk of outcome reporting biases	Criterion 7: Risk of outcome assessment biases	Overall judgement
	Operationalization by team							
	Specific factors (e.g. procedure type, device reuse, energy mix) affecting results	Differences in included procedures or settings after intervention/audit	Used for non-interventional studies. Incorrect or inconsistent classification of comparators	Used for interventional studies. Variations in staff behavior or protocols influencing outcomes	Inconsistent or non-standardized outcome measurement	Selective or incomplete reporting of environmental outcomes	Outcome assessors influenced by knowledge of exposure/intervention	Combined risk-of-bias rating based on criteria 1-7
Cunha Neves et al. (2023) [21] Portugal	Low risk of bias	Low risk of bias	Not Applicable	Low risk of bias	Low risk of bias	Low risk of bias	Medium risk of bias	Medium risk of bias
De Jong et al. (2023) [22] Netherlands	High risk of bias	Low risk of bias	Not Applicable	Low risk of bias	Medium risk of bias	Low risk of bias	High risk of bias	High risk of bias
Desai et al. (2024) [23] USA	Low risk of bias	Low risk of bias	Medium risk of bias	Not Applicable	Medium risk of bias	Low risk of bias	Medium risk of bias	Medium risk of bias
Elli et al. (2024) [24] Italy	High risk of bias	Medium risk of bias	Medium risk of bias	Not Applicable	Low risk of bias	High risk of bias	Medium risk of bias	Medium risk of bias
Fichtl et al. (2024) [25] Germany	High risk of bias	Low risk of bias	Not Applicable	Low risk of bias	Medium risk of bias	Low risk of bias	High risk of bias	High risk of bias
Gayam (2020) [26] USA	High risk of bias	Medium risk of bias	High risk of bias	Not Applicable	Medium risk of bias	High risk of bias	High risk of bias	High risk of bias
Gordon et al. (2021) [27] USA	Low risk of bias	Medium risk of bias	Not Applicable	Medium risk of bias	Medium risk of bias	Medium risk of bias	Medium risk of bias	Medium risk of bias
Grau et al. (2025) [28] France	Low risk of bias	Low risk of bias	Not Applicable	Low risk of bias	Low risk of bias	medium risk of bias	Medium risk of bias	medium risk of bias
Henniger et al. (2023) [29] Germany	Low risk of bias	Medium risk of bias	Not Applicable	Medium risk of bias	Medium risk of bias	Medium risk of bias	Medium risk of bias	High risk of bias
Henniger et al. (2023) [30] Germany	High risk of bias	Medium risk of bias	Not Applicable	Low risk of bias	Medium risk of bias	Low risk of bias	Medium risk of bias	High risk of bias
Jalayeri Nia et al. (2024) [31] UK	High risk of bias	Medium risk of bias	Medium risk of bias	Not Applicable	Medium risk of bias	Medium risk of bias	Medium risk of bias	High risk of bias
Jung et al. (2025) [32] South Korea	high risk of bias	Low risk of bias	Medium risk of bias	Not Applicable	Medium risk of bias	Low risk of bias	Medium risk of bias	high risk of bias
Klose et al. (2024) [33] Germany	High risk of bias	Medium risk of bias	Medium risk of bias	Not Applicable	Medium risk of bias	Medium risk of bias	Medium risk of bias	High risk of bias
Kojima et al. (2008) [34] Japan	High risk of bias	Low risk of bias	Not Applicable	High risk of bias	Medium risk of bias	Medium risk of bias	Medium risk of bias	High risk of bias
Lacroute et al. (2023) [35] France	Low risk of bias	Low risk of bias	Low risk of bias	Not Applicable	Medium risk of bias	Low risk of bias	Low risk of bias	Medium risk of bias
Lämmer et al. (2025) [36] Netherlands	high risk of bias	Low risk of bias	Low risk of bias	Not Applicable	Medium risk of bias	Low risk of bias	Medium risk of bias	high risk of bias
Le et al. (2022) [37] USA	Low risk of bias	Low risk of bias	Medium risk of bias	Not Applicable	Low risk of bias	Low risk of bias	Medium risk of bias	Medium risk of bias

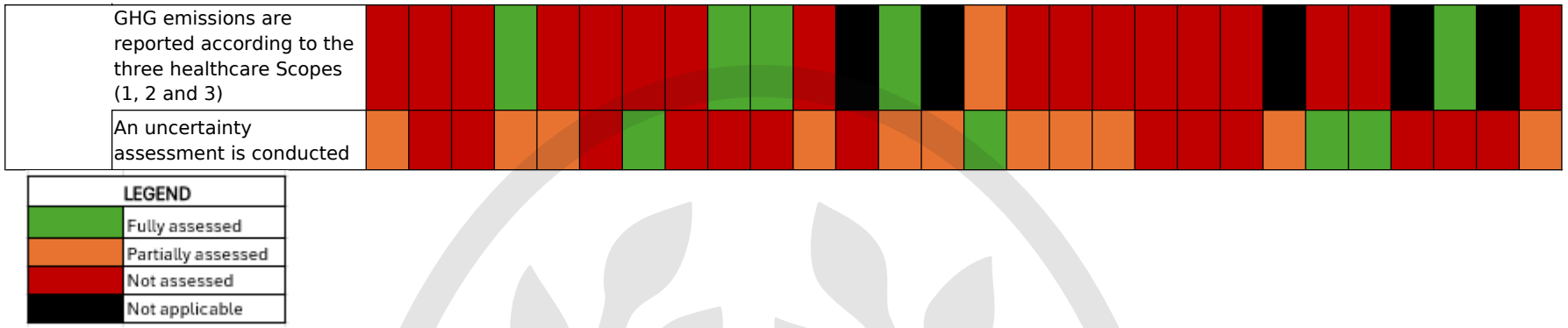
López-Muñoz et al. (2024) [40] Spain	High risk of bias	Low risk of bias	Medium risk of bias	Not Applicable	Medium risk of bias	Medium risk of bias	Medium risk of bias	High risk of bias
López-Muñoz et al. (2023) [3] Spain	High risk of bias	Low risk of bias	Not Applicable	Low risk of bias	Low risk of bias	Medium risk of bias	Medium risk of bias	High risk of bias
Lotter et al. (2025) [40] Australia	high risk of bias	Low risk of bias	high risk of bias	Not Applicable	Low risk of bias	Low risk of bias	Medium risk of bias	high risk of bias
Martín-Cabazuelo et al. (2024) [41] Spain	High risk of bias	Low risk of bias	Medium risk of bias	Not Applicable	Medium risk of bias	Medium risk of bias	Medium risk of bias	High risk of bias
Namburar et al. (2022) [42] USA	High risk of bias	Medium risk of bias	Medium risk of bias	Not Applicable	Medium risk of bias	Low risk of bias	Medium risk of bias	High risk of bias
Pioche et al. (2023) [43] France	High risk of bias	Low risk of bias	Medium risk of bias	Not Applicable	Medium risk of bias	Medium risk of bias	Medium risk of bias	High risk of bias
Pioche et al. (2024) [44] France	High risk of bias	Low risk of bias	Low risk of bias	Not Applicable	Medium risk of bias	Medium risk of bias	Medium risk of bias	High risk of bias
Ribeiro et al. (2024) [45] Portugal	High risk of bias	Low risk of bias	Medium risk of bias	Not Applicable	Medium risk of bias	Medium risk of bias	Medium risk of bias	High risk of bias
Rughwani et al. (2025) [46] India	high risk of bias	Low risk of bias	Low risk of bias	Not Applicable	Medium risk of bias	Low risk of bias	Medium risk of bias	high risk of bias
Vaccari et al. (2018) [47] Italy	High risk of bias	Low risk of bias	Low risk of bias	Not Applicable	Low risk of bias	Medium risk of bias	Medium risk of bias	High risk of bias
Zullo et al. (2023) [48] Italy	High risk of bias	Low risk of bias	Medium risk of bias	Not Applicable	Medium risk of bias	Medium risk of bias	Medium risk of bias	High risk of bias

Ref, reference; UK, United Kingdom; USA, United States of America.

Each CEECAT domain was adapted to GI endoscopy sustainability studies: study design (LCA, waste audit, carbon footprinting) was assessed for methodological appropriateness; scope and system boundaries for inclusion of relevant stages; data quality for completeness and reliability; analysis transparency for clarity of methods and assumptions; uncertainty/sensitivity for variability in energy use, product lifespan, or waste handling; conflicts of interest for potential stakeholder influence; and reporting completeness for absolute and normalized environmental impacts. Scoring followed these criteria to ensure consistent, transparent risk-of-bias assessment.

Table S8 – Quality assessment for included studies using ESGE's E-SPARE checklist

		[21]	[22]	[23	[24]	[25]	[26]	[27]	[28]	[29]	[30]	[31]	[32]	[33]	[34]	[35]	[36]	[37]	[38]	[39]	[40]	[41]	[42]	[43]	[44]	[45]	[46]	[47]	[48]
Introduction	A study hypothesis or objective is stated																												
Methods	The functional unit is defined																												
	The study (system) boundary is clearly defined																												
	The clinical setting, care pathway or departmental characteristics under analysis are clearly described																												
	The methodological approach used to assess environmental impacts is explicitly stated and justified (e.g. carbon footprinting, LCA)																												
	The environmental impacts chosen for assessment are defined and justified, using standard terminology and units of measurement																												
	Assumptions or exclusions are clearly stated and justified																												
	An inventory of all processes withing the system boundary is compiled and available to review																												
	Allocation methods are described and justified																												
	Emission factors sources are stated																												
Results	Endoscopic procedures or devices included in the analysis are characterized																												



ESGE, European Society of Gastroenterology; E-SPARE, endoscopic sustainability primary reporting essentials; GHG, greenhouse gas; LCA, life cycle assessment.

Table S9 – Quality assessment of included studies describing LCAs

Appraisal criteria	Indicator(s)	Operationalization by our research team - adapted from Kouwenberg et al. (2024) [20]	Gordon (2021) [27]	Grau (2025) [28]	Lämmer (2025) [36]	Le (2022) [37]	López Muñoz (2023) [39]	López Muñoz (2024) [38]	Lotter (2025) [40]	Martín Cabazuelo (2024) [41]	Pioche (2023) [43]	Pioche (2024) [44]
Phase 1: goal and scope (13 points)												
Study goal is clearly stated, including the study's rationale **(1)** intended application **(1)** and intended audience **(1)**	Transparency		2	2	2	2	3	2	2	2	2	2
LCA method is clearly stated **(1)**	Transparency	If the term LCA was not explicitly used, this item scored zero points	1	1	1	1	1	1	1	1	1	1
Functional unit is clearly defined and measurable **(1)** justified **(1)** and consistent with the study's intended application **(1)**	Consistency	No points were subtracted if the term “functional unit” was not explicitly used. Points were given based on a clear description of the unit of analysis. In case no intended application was mentioned (scoring item 1), consistency with the study’s aim was assessed.	3	2	3	2	1	2	2	3	2	2
The system studied is adequately described with clearly stated system boundaries **(1)**, life cycle stages **(1)**, and appropriate justification of any omitted stages **(1)**	Transparency; bias	Points for appropriate justification of any omitted stages were not given if the study listed only excluded elements, without an explanation of why these were excluded.	3	2	2	2	3	3	3	3	3	3
The system covers production **(1)** use/reuse **(1)** and disposal **(1)** of materials and energy	Internal validity, completeness	The original assessment tool included: “half mark if only for energy and vice versa,” which was unclear for our reviewers and left out of the assessment.	2	2	2	1,5	2	1,5	1	1,5	1,5	1,5
Phase 2: Inventory analysis (7 points)												
The data collection process is clearly explained, including the source(s) of foreground material weights and energy values **(1)**, the source(s) of reference data	Transparency; internal validity		3	2	3	3	3	3	3	3	3	2

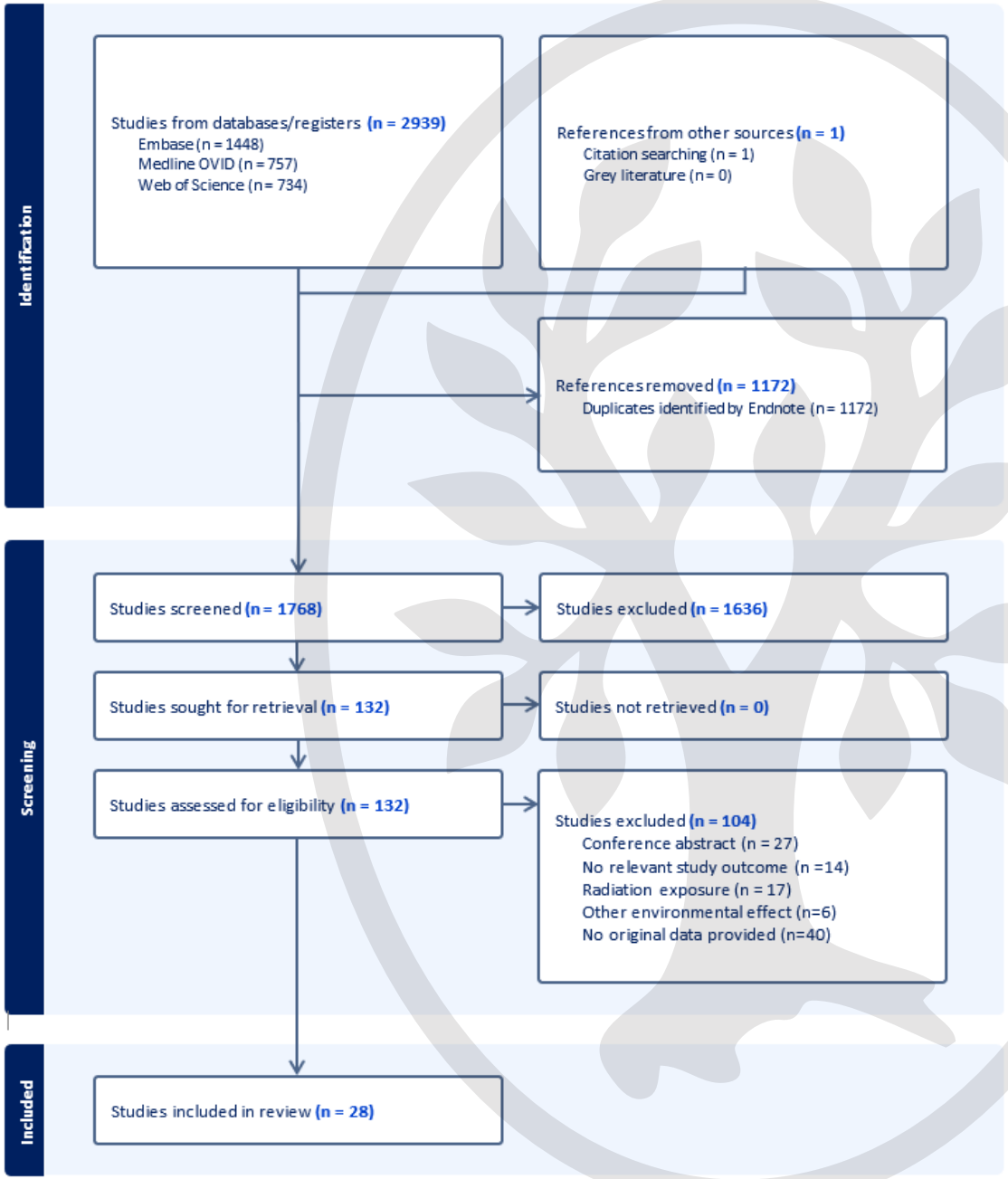
(e.g. inventory database) **(1)** and what data are included (e.g. production and disposal of unit processes **(1)**												
Representativeness of the data is discussed **(1)**, differences in electricity generating mix are accounted for **(1)** and the potential significance of exclusions or assumptions is addressed **(1)**	Internal validity; external validity	Point for electricity generating mix given if analyses were adjusted for local energy mix or if sensitivity to different energy mixes was assessed. Point for representativeness given only when explicitly mentioned with regard to either geographic, temporal, or technological representativeness, e.g., when prices were deflated. If geographical representativeness was only addressed in the context of the energy mix, only one point was given for "differences in electricity generating mix are accounted for." Point for addressing the potential significance of exclusions or assumptions given only if potential significance was explicitly stated, i.e., whether it potentially led to an under- or overestimation.	3	2	0	1	1	0	1	2	1	1
allocation procedures, where necessary, are described and appropriately justified **(1):** mark given if no allocation was used	Transparency; bias	This item was given a score of 1 if no substantial allocation was deemed necessary in the study.	1	1	1	1	1	1	1	1	1	1
Phase 3: Impact assessment (6 points)												
impact categories **(1)**, characterization method **(1)**, and software used **(1)** are documented transparently	Transparency	Given that all articles mentioned the term "carbon footprint" (because this was included in the literature search), 1 point was always given for "impact categories."	3	2	3	3	3	3	0	3	3	3
Results are clearly reported in the context of the functional unit **(1)** (0.5 if graphically, 0 if only	Consistency; transparen	If no functional unit was described in phase 1, this item was judged based on the way results were	1	1	1	1	1	1	1	1	1	1

normalized results were reported)	cy	presented in general.										
A contribution analysis is performed and clearly reported **(1)** and hotspots are identified **(1)**		A point was given for contribution analysis if the results were summed up and presented as a total footprint.	2	2	2	2	1	2	2	2	2	2
Phase 4: Interpretation (9 points)												
Conclusions are consistent with the goal and scope **(1)** and the potential impact of omissions or assumptions on the study's outcomes are described **(1)**	Internal validity; consistency	If no goal and scope were described earlier, this item was judged based on the clearness of the provided conclusion(s) in general.	1	1	1	2	2	2	1	2	2	1
Results are contextualized through the use of sensitivity analysis **(1)** and uncertainty analysis **(1)**	Internal validity	If the study did not explicitly mention “sensitivity” or “uncertainty analysis,” but presented ranges or standard deviations: 1 point was given for “uncertainty analysis.”	1	0	0	1	0	0	0	0	0*	1
Limitations are adequately discussed **(1)** and the potential impact of omissions or assumptions on the study's outcomes are described **(1)**	Bias	Only points given when the potential impact of the omission on the study’s outcomes were explicitly mentioned, i.e., whether the omission likely led to an under- or overestimation.	1	1	1	2	1	2	2	2	2	1
The assessment has been critically appraised (peer review if journal article or independent, external critical review if report/thesis(**(1)**	Bias	No point was given in the case of a letter to the editor or a commentary because these are generally not peer-reviewed. However, if an included letter is peer-reviewed, 1 point will be given.	1	1	1	1	1	1	1	1	1	1
Source(s) of funding and any potential conflict(s) of interest are disclosed **(1)** and are unlikely to be a source of bias **(1)**	Bias	No point was given for the first item if only conflict(s) of interest were disclosed but no source(s) of funding were reported.	0	2	2	2	2	2	2	2	0	1
		TOTAL (out of 35)	**28**	**24**	**25**	**27,5**	**26**	**26,5**	**23**	**29,5**	**25,5**	**24,5**
		Percentage	80%	69%	71%	79%	74%	76%	66%	84%	73%	70%

Based on: Drew, J. et al. (1997)[18] and Weidema, B. P. et al. (1997)[19]. LCA, life cycle assessment; SBCE, small bowel capsule endoscopy

** The article mentioned that a sensitivity analysis was performed, but no data is shown in the article.*

Figure S1 – PRISMA flow diagram of studies included and excluded in the systematic review



PRISMA, preferred reporting items for systematic reviews and meta-analyses.

PRISMA Abstract checklist

Section and Topic	Item	Checklist item	Reported (Yes/No)
TITLE			
Title	1	Identify the report as a systematic review.	Yes
BACKGROUND			
Objectives	2	Provide an explicit statement of the main objective(s) or question(s) the review addresses.	Yes
METHODS			
Eligibility criteria	3	Specify the inclusion and exclusion criteria for the review.	Yes
Information sources	4	Specify the information sources (e.g. databases, registers) used to identify studies and the date when each was last searched.	Yes
Risk of bias	5	Specify the methods used to assess risk of bias in the included studies.	Yes
Synthesis of results	6	Specify the methods used to present and synthesise results.	Yes
RESULTS			
Included studies	7	Give the total number of included studies and participants and summarise relevant characteristics of studies.	Yes
Synthesis of results	8	Present results for main outcomes, preferably indicating the number of included studies and participants for each. If meta-analysis was done, report the summary estimate and confidence/credible interval. If comparing groups, indicate the direction of the effect (i.e. which group is favoured).	Yes
DISCUSSION			
Limitations of evidence	9	Provide a brief summary of the limitations of the evidence included in the review (e.g. study risk of bias, inconsistency and imprecision).	Yes
Interpretation	10	Provide a general interpretation of the results and important implications.	Yes
OTHER			
Funding	11	Specify the primary source of funding for the review.	Yes
Registration	12	Provide the register name and registration number.	Yes

From: Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71

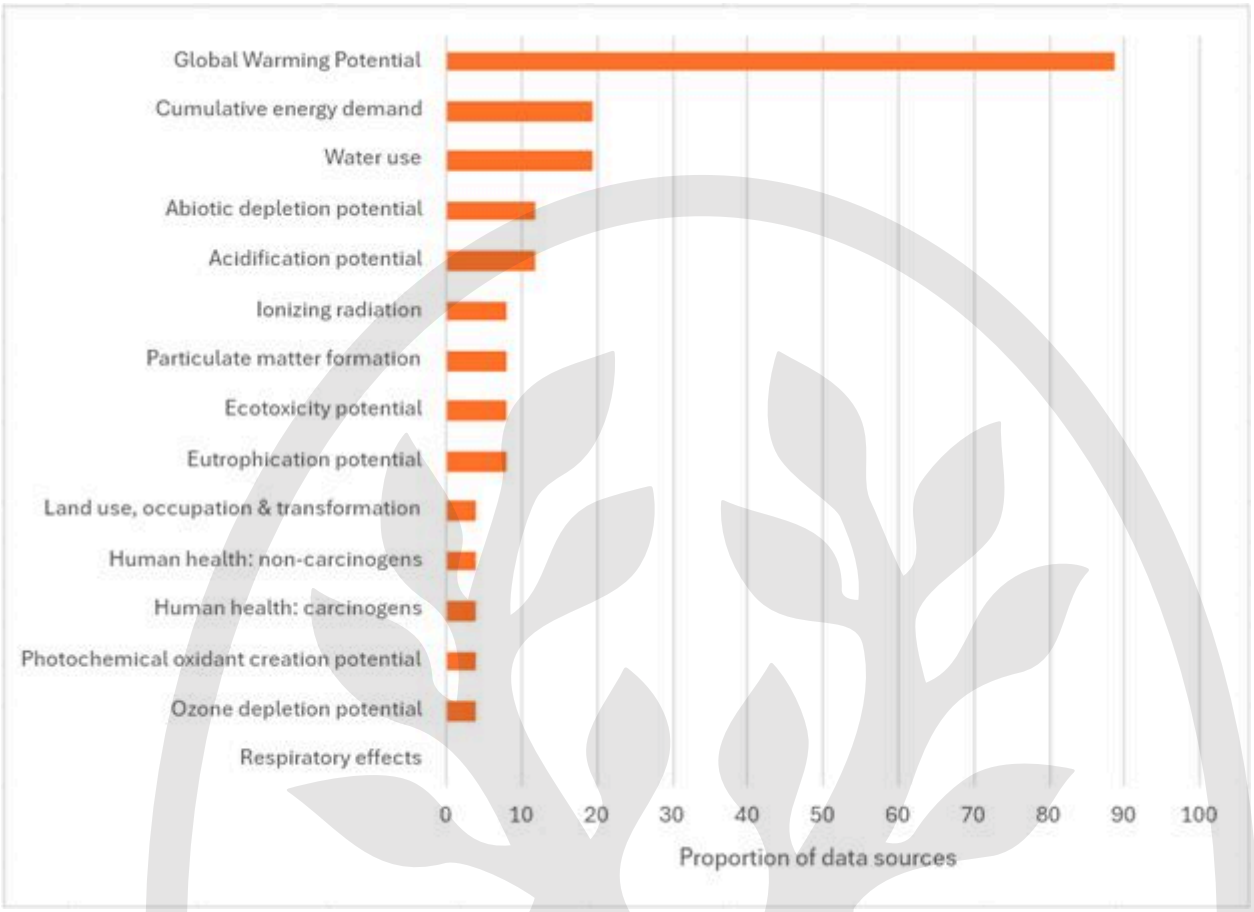
PRISMA checklist

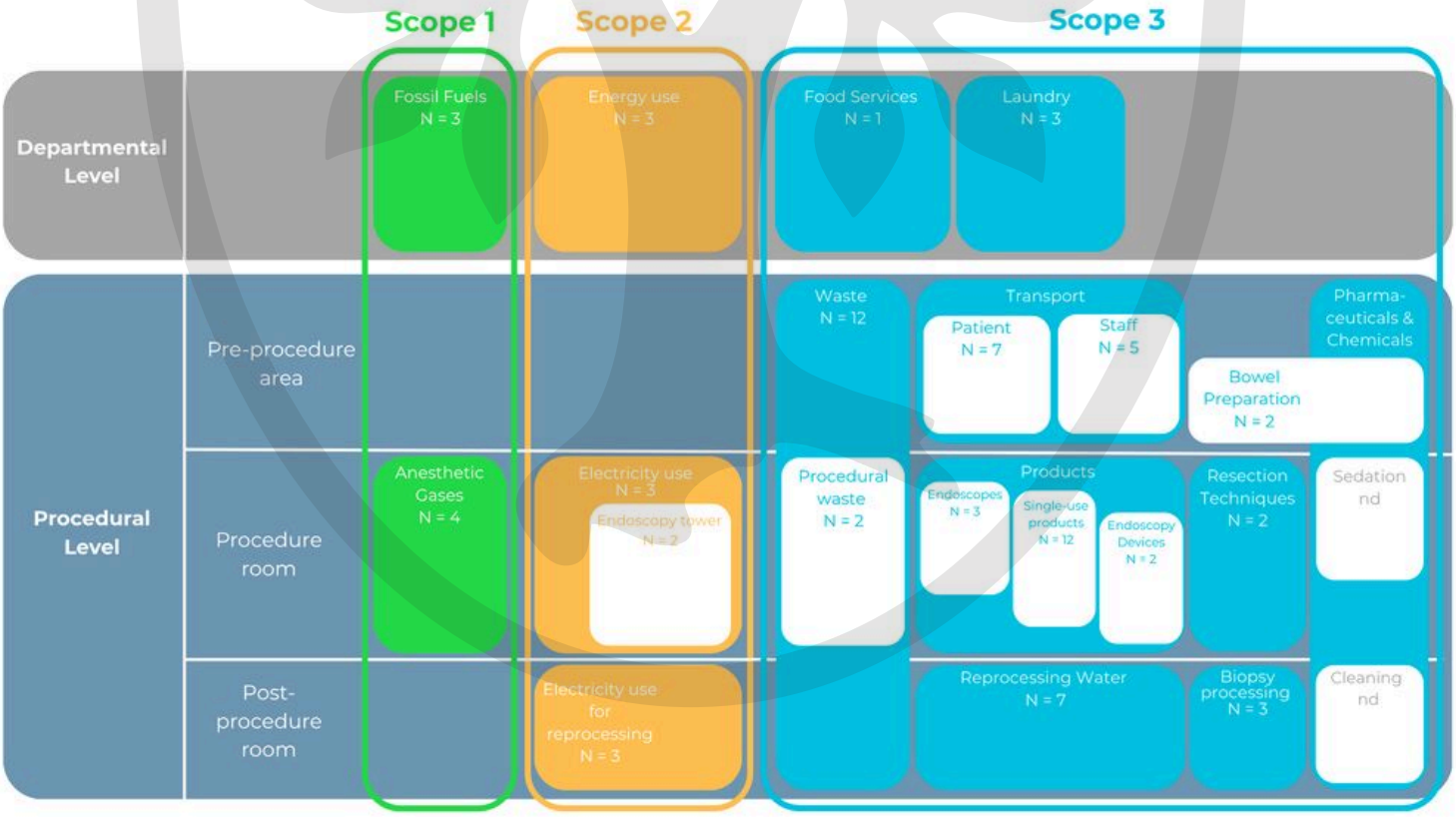
Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	1
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	3
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	3
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	5
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	5
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	5, Table S1, Figure S1
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	5
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	5-6
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	6
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	5-6
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	6
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	6
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	6
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	N/a
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	N/a
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	N/a
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	N/a
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	N/a
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	N/a
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	N/a

RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	7, Figure S1
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	7, Figure S1
Study characteristics	17	Cite each included study and present its characteristics.	7-9, Table 2, Table S2-S6
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	9, Table S9
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	7-9, Table 1
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	9, Table S7
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	N/a
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	N/a
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	N/a
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	N/a
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	N/a
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	10
	23b	Discuss any limitations of the evidence included in the review.	11
	23c	Discuss any limitations of the review processes used.	11
	23d	Discuss implications of the results for practice, policy, and future research.	11
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	4
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	4
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	N/a
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	11
Competing interests	26	Declare any competing interests of review authors.	11
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	N/a

N/a, not applicable

From: Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71





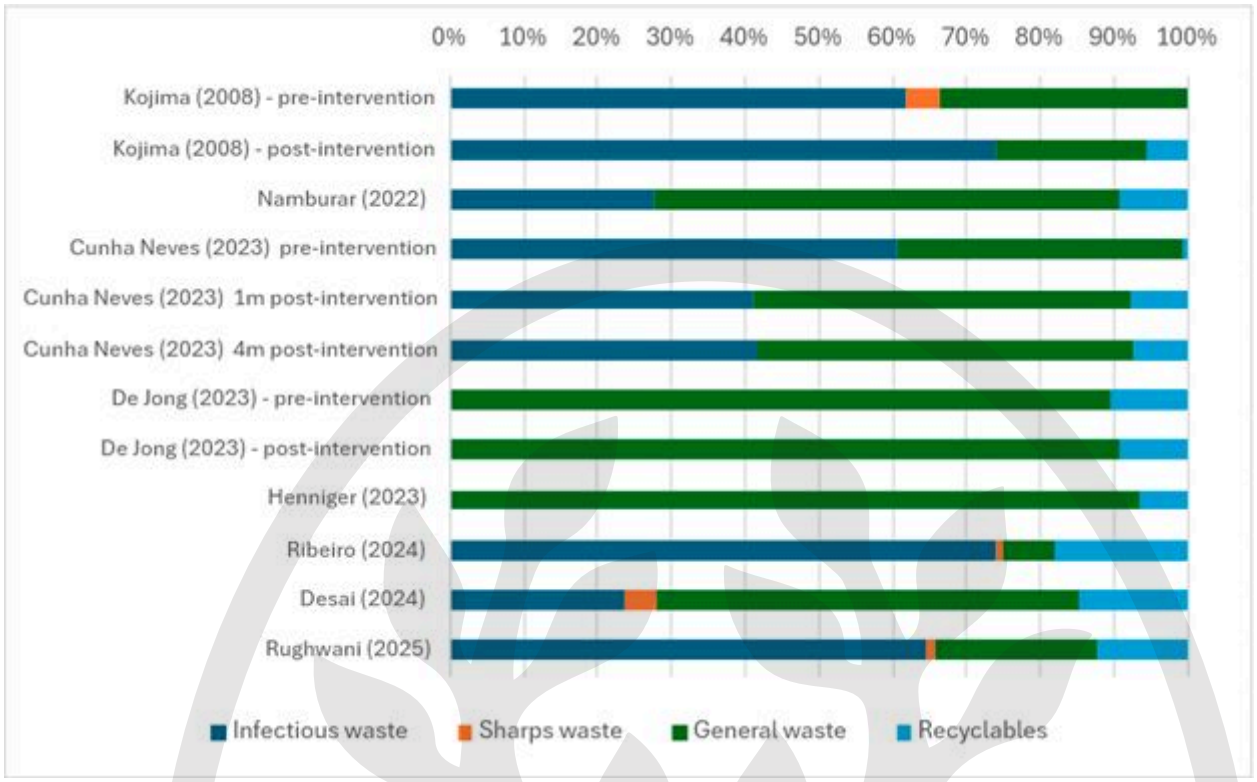
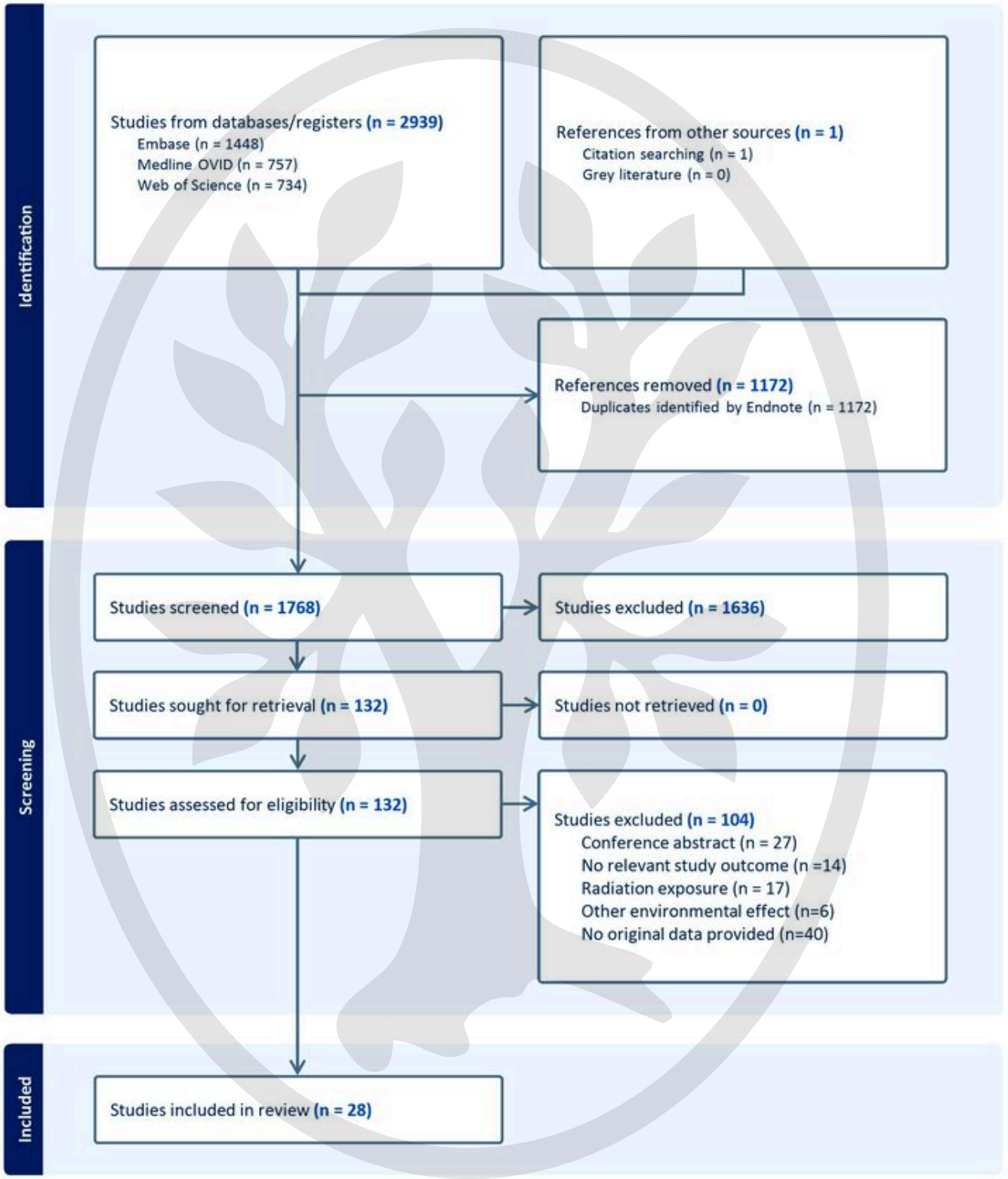


Figure S1 – PRISMA flow diagram of studies included and excluded in the systematic review



PRISMA, preferred reporting items for systematic reviews and meta-analyses.