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Environmental Sustainability of Clinical Laboratories: A Scoping Review

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Abstract

Introduction: The climate crisis presents a complex and growing challenge for healthcare systems around the world. Healthcare systems can contribute to substantial global emissions, with the UK's National Health Service (NHS) alone responsible for 4–5% of the country's total carbon footprint. A wide range of clinical disciplines have already begun to assess and design interventions to tackle this issue. However, clinical and diagnostic laboratories remain underexplored.

Aims: What studies have been undertaken to assess and improve the environmental impact of clinical laboratories?

Methods: This scoping review undertook a multi-database search from date of inception to 5th February 2024. All primary studies that assessed the environmental outcomes of clinical laboratories were included. Studies were screened and data extracted by one reviewer with a 10% verification process at each stage. Studies were assessed based upon year of publication, geographical region, interconnectivity and area and type of clinical laboratory or test.

Findings: There has been some longstanding interest in understanding the environmental impact of clinical laboratories, and this field of investigation has gained popularity within the scholarly community in the last decade. Despite this recent increase in popularity there is a relatively limited number of intervention studies aimed at improving sustainability within clinical laboratories. Most research in this area originates from the United States, United Kingdom, and Australia, although the topic appears to be of global scholarly interest. There is limited interconnectivity of studies included in this review.

Studies in this field have primarily been conducted at the clinical laboratory level, with a focus on quantifying waste in kilograms, measuring carbon dioxide equivalent (CO_2e) emissions, and categorising laboratory waste by type. To a lesser degree these outcomes have been assessed for specific clinical tests. Across both clinical laboratory and specific test assessments there is notable heterogeneity in both methods used, and areas explored.

Discussion: While this scoping review highlights a growing interest and awareness in this important field, the diversity of reported outcomes and the limited interconnectivity of studies indicate that it remains a developing area. The lack of consensus in methodologies and outcome measures suggests that establishing a baseline analysis remains a distant goal. Ideally, future efforts should prioritize improving the assessment of individual laboratory tests, fostering greater standardization, and enhancing repeatability to strengthen the reliability of environmental impact evaluations.

Introduction

The ongoing climate crisis presents escalating challenges (United Nations, 2025), influencing various sectors, including medical practice (Freifeld, Todd, & Khan, 2023; Levinson, 2024) and scientific research (Klingelhöfer et al., 2020). The crisis will mandate adaptation both at the clinical level as environmental changes affect human health (Bhopal & Shrivastava, 2021), as well as the operational level as climate variation impacts the infrastructure that supports health services (Lokotola, 2023). In the UK, the National Health Service (NHS) was the world's first national health provider to declare a net-zero policy, with a variety of pathways mapped depending on level of action taken (NHS England, 2022). This is crucial to the UK's net-zero ambitions, as the NHS is responsible for an estimated 4-5% of the UK's carbon emissions (NHS England, 2020b).

Work has begun to look at health systems infrastructure (World Health Organization, 2024), as well as many of the clinical specialties that make-up a complete health system (Gaetani et al., 2024; Gordon, 2024; Li Valverde et al., 2024). While challenging, notable academic and policy progress has been made in a variety of such specialties, such as surgery (Gupta, 2023), general practice (Nunes et al., 2025), emergency medicine (Spruell et al., 2021), and research laboratories (Farley, 2022). Such research has led not only to estimated impacts of clinical specialties, but burgeoning programmes aimed at mitigating the emissions associated, such as the Royal College of Emergency Medicine's GreenED programme (Royal College of Emergency Medicine, 2024). Clinical and diagnostic laboratories have yet to undergo such a revolution.

The requirement of *in vitro* diagnostics (IVDs) has increased significantly globally (MedTech, 2022), in part due to the COVID-19 pandemic (World Health Organization, 2025). Each year, approximately 14 billion tests are conducted in the US (Centers for Disease Control Prevention, 2024), 1.2 billion in the UK (NHS England, 2020a), and 500 million in Australia (Public Pathology Australia, 2019). Market research estimates that the global diagnostic laboratory market will increase from $297 billion in 2021 to $514 billion by 2028, representing an immense rate of growth (BCC, 2023). IVDs take place within laboratory facilities, which in themselves have the potential to be energy intensive due to their significant heating, cooling, and particularly ventilation requirements (Butler, Johnson, & Boone, 2013; Ezzelle et al., 2008). Beyond energy, IVDs require analytical equipment which comes with the potential of ecological impact (Huang & Ciesla, 1992), as do the immense volumes of single-use plastics (Lee, Ellenbecker, & Moure-Eraso, 2002). IVDs also can require transport or delivery, which can increase their ecological impact (Araujo et al., 2014).

The predicted growth of IVDs has the potential to significantly increase the environmental impact of clinical laboratories. This is driven by the resource-intensive nature of laboratory operations, including environmental requirements, specialist equipment, waste products, transport and energy costs. As a result, it is imperative to better understand what research has been conducted to date.

Recent systematic reviews in this field have examined the environmental impact of broader healthcare systems (Keil et al., 2024) and hospitals (Ghali et al., 2023) or assessed interventions aimed at reducing their environmental footprint (Braithwaite et al., 2024; Seppänen & Or, 2025). Previous review papers have highlighted the need for environmental assessment and interventions

at a specific clinical laboratory level (Devis et al., 2025; Rai et al., 2024; Welburn, 2024). Despite this recognition, no comprehensive synthesis currently exists on the environmental impact of clinical laboratories, or the interventions implemented to mitigate their effects.

Aims/questions:

This scoping review aims to answer two questions. These are:

1. Q1: What studies have been undertaken assessing the environmental impact of clinical laboratories?

2. Q2: What interventions have been studied to mitigate the environmental impact of clinical laboratories?

Methods

This scoping review was conducted following methodological guidance provided by (Peters et al., 2020) and (Levac, Colquhoun, & O'Brien, 2010). This scoping review is reported in accordance with the PRISMA Extension for Scoping Reviews (PRISMA-ScR) guidance (Tricco et al., 2018).

Search

The following databases were searched on 5th February 2024: MEDLINE (Ovid), Embase (Ovid), Environment Complete (EBSCOhost), and Web of Science (indexes: SCI-EXPANDED; SSCI; AHCI; CPCI-S; CPCI-SSH; ESCI). Search terms were identified by the review team and included a combination of relevant subject headings and keywords. The search strategy was developed by an information specialist (CH) and was adapted for each database. The search strategies used for each database can be found in Appendix 1. No date limits were applied, but searches were limited to studies in English. References were downloaded into EndNote and duplicates were removed before being uploaded into Rayyan for screening (Ouzzani et al., 2016). Backwards citation searching using Web of Science was conducted for included papers to identify additional studies.

Study selection

Any type of primary study which assessed any kind of environmental outcomes for clinical laboratories was included. For the purposes of this review clinical laboratories were defined as healthcare facilities providing a wide range of laboratory procedures which aid the physicians in carrying out the diagnosis, treatment, and management of patients (Bayot, Lopes, & Zubair, 2024). This definition was extended to include the screening for disease, as well as the use of Point of Care testing (POCT), which use similar technologies and often come under the operational management of clinical laboratories.

Title/abstract screening was conducted by a single reviewer using Rayyan (Ouzzani et al., 2016). Study selection was piloted with 10% of the titles and abstracts being screened by five reviewers. A Kappa Score was calculated to assess reviewer agreement during this pilot process, and substantial agreement (0.61 - 0.80 agreement) between all reviewers was needed before single screening of the remaining references continued (McHugh, 2012). Full paper screening followed the same 10% verification process and reasons for exclusion at the full paper screening stage were documented and recorded.

Data extraction (selection and coding)

After the 10% verification process data extraction was performed by one reviewer using a pre-piloted form. Reviewers used Microsoft Copilot AI (generative artificial intelligence software) [Azure OpenAI-powered AI: 01/04/24 - 01/09/2024] to verify the data items extracted (Hill, Harris, & Clegg, 2024). The data items extracted included: year of publication, country of study, city/town, study type, study aims, clinical setting, single or multi-centre, population (description of laboratory diagnostics or clinical laboratory activities under investigation), sample size, diagnostic focus, specimen and test types, outcomes, economic evaluation, and description of interventions implemented to reduce environmental impact, type of intervention, intervention description, control group where applicable.

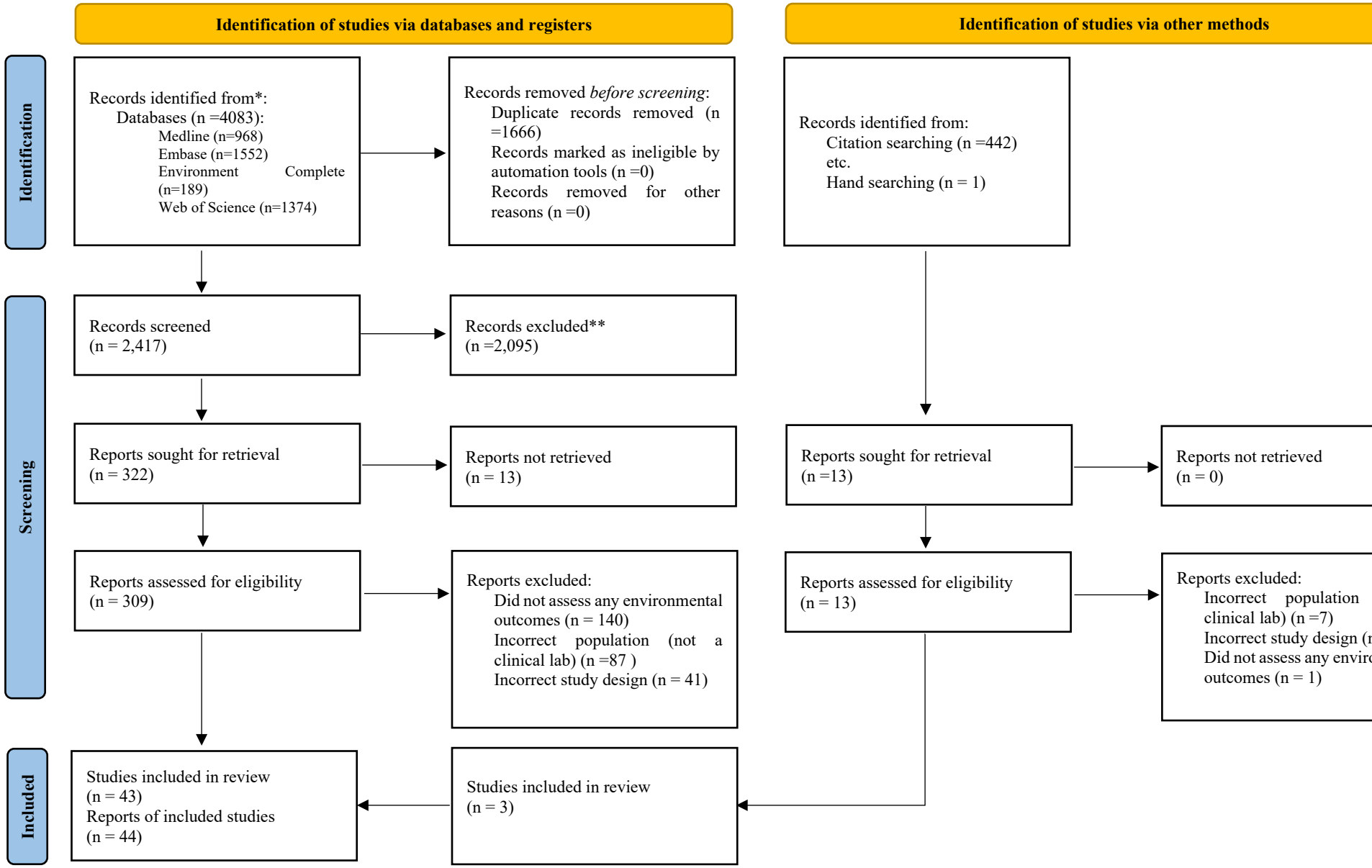
Strategy for data synthesis

Given the wide variation in study design, interventions, and outcomes, a narrative synthesis approach was used to organize the review findings. Bar charts were employed to analyse the growth in the number of studies per year over time. A geographical map was utilized to pinpoint the regions of the world that have explored this area and investigated interventions to reduce the environmental impacts of clinical laboratories (Samarasundera et al., 2012). Additionally, a citation map was employed to examine the interrelationship of citations within this field using Litmaps' citation mapping software (Litmaps, 2024). Individual study characteristics was described based upon two global categories of clinical laboratory assessment/interventions and specific tests.

Results

Database searches yielded 2,417 unique citations after duplicate removal, with 322 full-text papers retrieved following title and abstract screening. After full paper screening 40 studies (40 primary papers and one link to paper) met the inclusion criteria for the scoping review. Screening the references of the included studies led to the review of an additional 442 titles and abstracts, with one paper identified through hand searching. This process resulted in the screening of 13 full-text papers, from which three additional studies were included. This resulted in 43 studies (43 primary papers and one link to paper) being included in this review (figure 1).

During abstract and title screening the review team were able to achieve a substantial agreement within one round of consensus development (% of agreement: 98.8 – 99.6, Cohen's k: 0.65 – 0.90). Two rounds of consensus building were required during full paper screening to reach substantial agreement (% of agreement: 90.3 – 96.8, Cohen's k: 0.61 - 0.89). The primary reason for exclusion during full-text screening was the lack of reporting on environmental outcomes (n = 141). This was followed by studies that did not assess a clinical lab (n = 94) and those with inappropriate study designs (n = 43).


Identification of studies via databases and registers
Identification of studies via other methods
Identification
Screening
Included
Records identified from*:
Databases (n =4083):
Medline (n=968)
Embase (n=1552)
Environment Complete (n=189)
Web of Science (n=1374)
Records removed *before screening*:
Duplicate records removed (n =1666)
Records marked as ineligible by automation tools (n =0)
Records removed for other reasons (n =0)
Records identified from:
Citation searching (n =442)
etc.
Hand searching (n = 1)
Records screened
(n = 2,417)
Records excluded**
(n =2,095)
Reports sought for retrieval
(n = 322)
Reports not retrieved
(n = 13)
Reports sought for retrieval
(n =13)
Reports not retrieved
(n = 0)
Reports assessed for eligibility
(n = 309)
Reports excluded:
Did not assess any environmental outcomes (n = 140)
Incorrect population (not a clinical lab) (n =87)
Incorrect study design (n = 41)
Reports assessed for eligibility
(n = 13)
Reports excluded:
Incorrect population
clinical lab) (n =7)
Incorrect study design (n
Did not assess any enviro
outcomes (n = 1)
Studies included in review
(n = 43)
Reports of included studies
(n = 44)
Studies included in review
(n = 3)

Temporal Analysis of Studies on Clinical Laboratories' Environmental Impact

The number of studies per year evaluating the environmental impact of clinical laboratories is presented in Figure 2. The topic area of environmental impact of clinical laboratories was first assessed in 1975 (Pragay, 1975). For the following three decades (1975 – 2004) a relatively low number of studies were published (11.6%, n = 5). Subsequently, there has been a notable growth in the number of publications during the last 20 years, with 10 studies (23.2% of studies identified) published between 2005 to 2014 and 27 studies (65.1% of studies identified) between 2015 and 2024. The first intervention study was published in 2012, and the remaining five studies were published in 2022 and 2023.

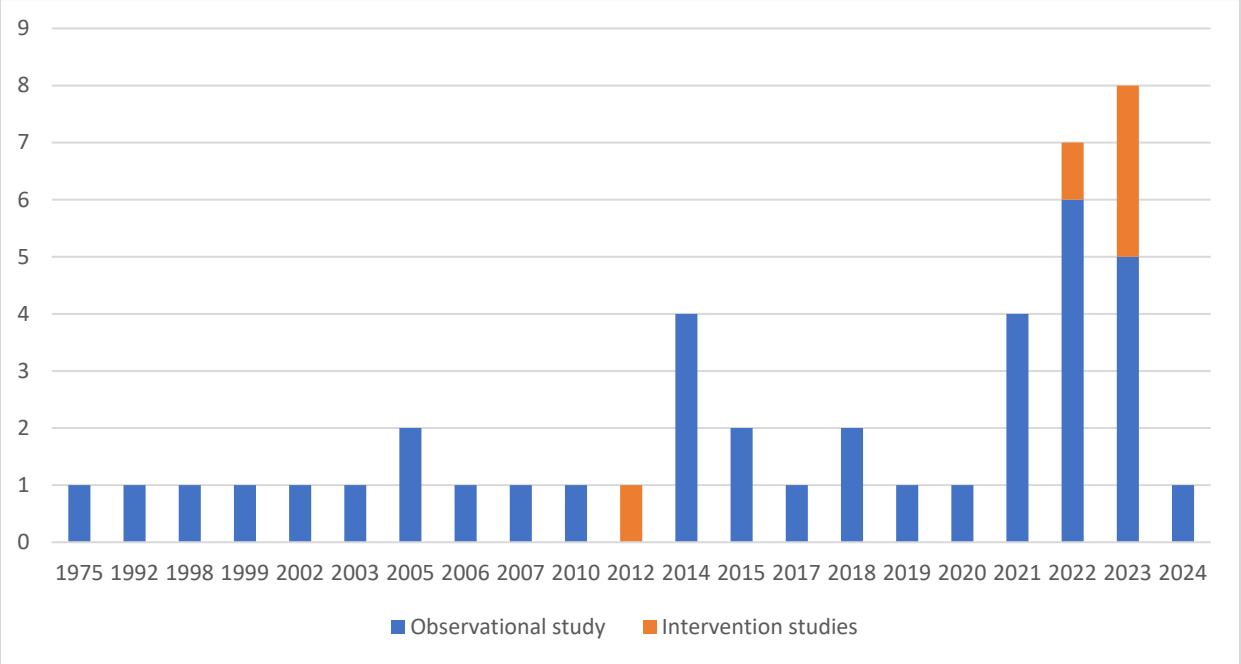


Figure 2: number of studies per year *evaluating the clinical impact of clinical laboratories. *inclusion dates for the literature search ran until February 5th 2024,*

Geographical Distribution of Research on Clinical Laboratory Environmental Impact

Exploring the geographical locations of the studies, nearly half were completed in three countries the United States (n = 9), United Kingdom (n = 6) and Australia (n = 6) (Figure 3 & Table 1 to 5). It is important to note that of these 21 studies, 15 were published in the last 10 years.

The second most common regional areas were Greece (n = 2), Germany (n = 2), India (n = 2), and Brazil (n = 2). Despite the relatively geographically clustered nature of the studies, there has been a wide range of single studies carried out in multiple countries, including Mexico, Jordan, Ethiopia, Poland, France, Iran, Pakistan, Sao Tome and Principe, Colombia, Canada, Thailand, Togo, Turkey, and the Netherlands.

Figure 3: Geographical location of included studies

Citation Patterns in Research on the Environmental Impact of Clinical Laboratories

The Litmaps citation map illustrates the current body of evidence evaluating the environmental impact of clinical laboratories and their citation relationships (see Figure 4 for Litmaps citation map of all included studies). Out of the 43 included studies only two studies were unable to be identified using the Litmap software. Of these 41 studies, only 14 studies (34.1%) cited previous research within this domain.

Externally (number of all citations of included studies), the included studies vary in the number of citations, with an interquartile range of 14 citations. The lower quartile (Q1) shows that 25% of the articles have 3 or fewer citations, while the upper quartile (Q3) indicates that 75% have 17 or fewer citations (Range = 0 to 308 citations). Out of the 41 included studies, the median number of citations was 10.

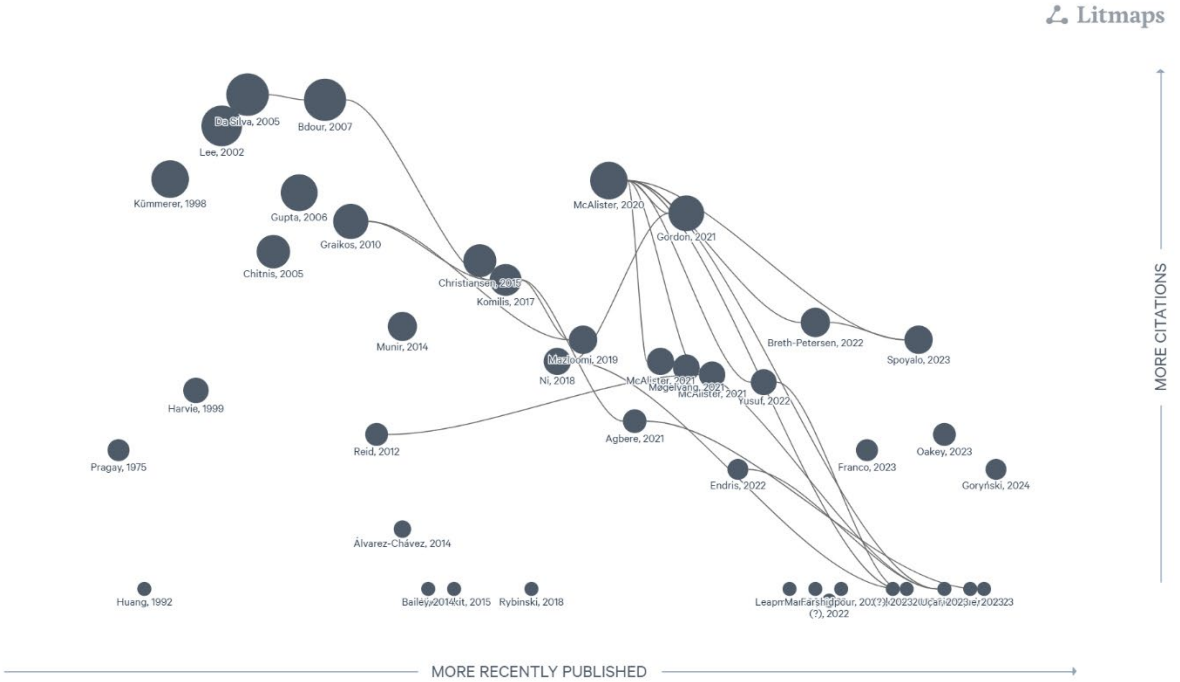


Figure 4: Litmaps citation map of all included studies. This citation map visually represents each study as a circle (node), with lines (edges) indicating citation relationships between them. The horizontal position reflects the year of publication, while the vertical position corresponds to the total number of citations each paper has received.

Stuthe vertical position corresponds to the total number of citations each paper has received dy

characteristics

Out of the 43 included studies, the assessment of environmental impact of laboratory testing was undertaken either at a clinical laboratory level [Clinical Laboratory-Wide Environmental Assessment] (n = 28) or for a specific clinical test (n = 15).

Clinical laboratory level - Observational studies

Of the 28 studies at the clinical laboratory level, 24 were observational studies, and four were intervention studies (Table 1). Among the 24 observational studies assessing the environmental impact of clinical laboratories, the majority evaluated the environmental impact of laboratory testing at a specific point in time, utilising either a retrospective cross-sectional design (n = 16) or a mixed-methods approach combining qualitative and cross-sectional data (n = 6). The remaining two studies that assessed the environmental impact of clinical laboratories at a clinical laboratory level presented environmental impact data collected using a cross-sectional design, which was then utilized as part of a simulation scenario aimed at reducing environmental impact (Bailey et al., 2014; Oakey et al., 2023).

The assessments of environmental impact at the clinical laboratory level were conducted in various care settings: secondary care (n = 8), tertiary care (n = 6), private independent laboratory (n = 5), secondary and tertiary care (n = 2), primary care (n = 2), and across primary, secondary, tertiary, and private independent laboratory (n = 1).

At a specific clinical laboratory level setting (primary, secondary, tertiary, private independent laboratory) there was limited commonality of reporting of environmental outcomes. Among the 24 studies that assessed the environmental impact at the clinical laboratory level, there was limited consistency in the metrics used. The most common measurement was laboratory waste quantified in kilograms (n = 12), followed by carbon dioxide equivalent (CO_2e) emissions (n = 5), laboratory waste categorised by type and measured in kilograms or litres (n = 4), and energy usage reported in kilowatt-hours (kWh) (n = 3). In addition to these outcomes, there were 14 additional varying outcomes reported in two or fewer studies. Additionally, three studies evaluated the financial costs at the clinical laboratory level. These costs included disposal expenses, potential cost savings from recycling, overall cost increases, driving and vehicle costs, partial cost offsets from cycle courier tasks, and the cost of decontaminating chemical waste.

Table 1 characteristics of Clinical laboratory level - Observational studies

Author	Country of study	Aims of the study	Study design	Clinical setting	Sample size	Environmental outcomes

(Alvarez-Chavez et al., 2014)	Mexico	Investigating potential sources of mercury pollution originating from clinical laboratory discharges, using an exploratory approach	Retrospective cross-sectional study	Secondary care	4 Hospitals clinical laboratories	Quantification of mercury in waste residues of autoanalysers
(Gupta & Boojh, 2006)	India	The present study pertains to the biomedical waste management practices at Balrampur Hospital, a premier healthcare establishment in Lucknow, in North India.	Case study (qualitative, case study observational and cross-sectional data)	Secondary care	Pathology waste - 1 week - reporting daily average	Waste in kg.
(Hang et al., 2023)	Australia	This initiative will review all facets of operations applicable to a biochemical genetics laboratory by: (1)	Mixed methods (cross-sectional and qualitative)	Secondary care	Not specified	Energy use in kWh, and CO_2e

		determining the current state of sustainability practices and understand staff perception, (2) identifying the largest stream of waste/carbon footprint for targeted mitigation strategies, and (3) identifying opportunities to incorporate sustainability in laboratory operations.				
(Harvie, 1999)	USA	Collaborative project between the study hospitals and Western Lake Superior Sanitary district to minimise mercury discharge from	Mixed methods (cross-sectional and qualitative)	Secondary care	Collection of unspecified number of samples over a 24hr period and 2 x 100 mL of supernatant of the treated mercury waste, which goes	Waste water mercury content

		hospital wastewater			to wastewater.	
(Kummerer et al., 1998),	Germany	To determine the AOX content in hospital wastewater as author was unaware of any such existing data	Retrospective cross-sectional study	Secondary care		Concentrations of Adsorbable organically bound halogens (AOX) in waste water effluent
(Lee, Ellenbecker, & Moure-Eraso, 2002)	USA	To analyse the recycling potential of plastic wastes generated by health care facilities	Retrospective cross-sectional study	Secondary care	Eight facilities (five city hospitals and medical centres, three animal hospitals)	Sources, disposal costs, plastic content of medical wastes, components, sources, types, and amounts of medical plastic wastes, recycling potential (Disposal costs and potential cost savings from recycling)
(Pragay, 1975)	United States	Assessing pollutants (solid and liquid wastes) discharged by clinical chemistry	Mixed methods (cross-sectional and qualitative)	Secondary care	Number of hospital sites has not been specified, but the data has been collected	Quantification of harmful elements in laboratory wastewater (Cost of decontamination of

		laboratories in New York and suggesting guidelines for their disposal			from local hospitals in the buffalo metropolitan area	chemical wastes)
(Yusuf et al., 2022),	Netherlands	Quantify carbon impact of diagnostic lab	Retrospective cross-sectional study	Secondary care	1320 beds of a hospital worth of tests	CO_2e & energy in W
(Bailey et al., 2014)	United Kingdom	Investigating the effects of temporal consolidation (the intentional delay) of hospital laboratory samples / equipment for couriering to people and health care institutions worldwide. This was carried out with an aim to reduce carbon emissions and improve operational efficiency.	Simulation	Tertiary care	476 courier records over a 3-month period	Vehicle emissions Journey distances Number of vehicles used fuel consumption

(Chitnis, Vaidya, & Chitnis, 2005)	India	Audit of biomedical waste is required to understand the type and quantity of waste generated. It helps in formulation of the plan for segregation, waste handling and management	Retrospective cross-sectional study	Tertiary care	6 month audit. 475 daily outpatients and 250 inpatients.	Laboratory waste was categorised by type and measured in kg or L.
(Christiansen et al., 2015)	Germany	Assess the time dependent course and weekly sum of the demand for electrical energy due to medical laboratory plug loads.	Retrospective cross-sectional study	Tertiary care	10,000 pieces of equipment	Average electricity consumption in kWh/week
(Munir, Batool, & Chaudhry, 2014)	Pakistan	The main objective of this research was to determine the type of waste generated its quantity and compositio	Retrospective cross-sectional study	Tertiary care	The study analysed waste from different departments and wards of the hospital over seven days.	Laboratory waste in kg, broken down by waste type

		n in hospital.				
(Wiwanitkit & Wians, 2015)	Thailand	Estimate carbon impact of a single lab and then project it further. Very limited data.	Retrospective cross-sectional study	Tertiary care	One lab	CO_2e
(Uçar, 2023)	Turkey	To assess the impact of sample rejection rates (SRRs) on laboratory sustainability by calculating the carbon footprint and medical waste generated due to rejected samples.	Retrospective cross-sectional study	Tertiary care	Approximately 4 million samples accepted in 2022, with approximately 77,000 samples rejected.	Carbon footprint (CO_2e), and medical waste generated.
(Araujo et al., 2014)	Brazil	Investigating the environmental impact of laboratories' activities on the ecosystem in 2013 by measuring	Retrospective cross-sectional study	Independent clinical laboratory	Not stated	Water consumption (m3), electricity (kW), paper consumption (sheets), waste (kg), fuel (L)

		consumption of natural resources, fossil fuel use for transportation, plastic bag, biomedical and solid waste, paper and electronic waste recycling				
(Da Silva et al., 2005)	Brazil	The primary aim of this study was to evaluate the actual situation of medical waste management in the cities located in the Vacacaı´ river basin in the south of Brazil. An inventory of healthcare facilities was performed, the main aspects of medical wastes management were	Mixed methods (cross-sectional and qualitative)	Independent clinical laboratory	Not stated	Laboratory waste measured in kg

		analysed, and the amount of residues generated by the facilities was estimated				
(Mazloomi et al., 2019)	Iran	The purpose of the present work was to evaluate the quantity and quality of clinical laboratory wastes in the city of Ilam, Iran.	Retrospective cross-sectional study	Independent clinical laboratory	Yearly amount of waste generated from the 8 laboratories	Laboratory waste in kg, broken down by waste type
(Agbere et al., 2021)	Togo	To assess the management of solid biomedical waste produced by biomedical laboratories in Togo	Mixed methods (cross-sectional and qualitative)	Independent clinical laboratory	82 public and private biomedical analysis laboratories.	Waste in kg.
(Komilis, Makroleivaditis, & Nikolakopoulou, 2017)	Greece	To investigate the generation rate and composition of solid medical wastes produced by private medical microbiolo	Retrospective cross-sectional study	Independent clinical laboratory	The study involved seven private medical microbiology laboratories with capacities ranging from 8 to 88	Waste in kg and percentage of hazardous (infectious) and non-hazardous (urban type) wastes.

		gy laboratories.			examinees per day.	
(Bdour et al., 2007),	Jordan	To assess medical waste management practices in 14 healthcare facilities in Irbid, Jordan	Retrospective cross-sectional study	Secondary and tertiary	14 healthcare facilities	Laboratory waste measured in kg
(Endris, Tamir, & Sisay, 2022)	Ethiopia	The purpose of this study was to assess the rate of biomedical waste generation, management practices, and associated factors in public healthcare medical laboratories in Addis Ababa, Ethiopia.	Retrospective cross-sectional study	Secondary and tertiary	Not stated	Laboratory waste was categorised by type and measured in kg
(Oakey, Martinez-Sykora, & Cherrett, 2023)	UK	The aim was to improve the logistics of healthcare diagnostic sample this	Prospective modelling study	Primary care	One hospital in Southhampton and one hospital on the Isle of Wight. 97 primary	CO_2e tailpipe emissions (Overall Cost Increase, Reduction in Driving and

		scoping review has some collection by combining driving and cycling to reduce transit time, minimise the use of fossil-fuelled vehicles and enhance service quality.			care sites in Southhampton and 22 primary care sites on the Isle of Wight.	Vehicle Costs, Partial Cost Offset from Cycle Courier Tasks)
(Graikos et al., 2010)	Greece	To determine the composition and production rate of medical waste from the health care facility of the social insurance institute	Retrospective cross-sectional study	Primary care	2817 patients for the clinical pathology laboratory	Waste in kg and kg/d
(Pereira & Dias-Ferreira, 2023)	Sao Tome and Principe	The aim was to gain knowledge of the current state of management of waste from clinical analysis	Retrospective cross-sectional study	Primary, secondary, tertiary and private	14 clinical analysis laboratories	Laboratory waste measured in kg

		laboratories in Sao Tome and Principe.				

Clinical laboratory level - Experimental studies

Four of the studies were intervention studies at a clinical laboratory level, based in tertiary care (n = 2), secondary care (n = 1) and in a private independent laboratory (n = 1) setting. These employed either a retrospective before-and-after study design (Anonymous et al., 2022; McAlister et al., 2021; Reid et al., 2012) or experimental design (Ramírez et al 2023). Across the four studies, the interventions focused on four main approaches: resource recycling and waste reduction (e.g., reagents, plastic, and water; Anonymous et al., 2022; Reid et al., 2012; Ramírez et al 2023), energy efficiency and renewable energy integration (solar panels and insulation; Anonymous et al., 2022), and operational changes (limiting non-urgent testing and enhancing staff engagement; McAlister et al., 2021; Reid et al., 2012). These efforts collectively aimed to promote environmental sustainability and operational efficiency**.**

For the environmental outcomes assessed, a similar level of heterogeneity is observed as in the observational studies, with each study evaluating slightly different outcomes. These include reductions in reagent usage, recycling rates, electricity savings, CO_2e savings from tests performed, quantification of dyes found in laboratory wastewater, and the quantification of recycling rates and waste sent to landfill. Two of the studies recorded the economic impact of the environmental intervention (total saving and saving per year).

Table 2. Study Characteristics of Experimental Studies at the Clinical Laboratory Level

Author	Country of study	Aims of the study	Study design	Clinical setting	Sample size	Intervention	Environmental outcomes
(Anonymous, 2022)	USA	To implement green initiatives in their dermatopathology lab to reduce their environmental impact	Retrospective before and after study	Tertiary	Not stated	Recycling of reagents such as formalin, xylene, and alcohol. Shredding of plastic,	Reduction in reagent usage, recycling rates, electricity savings, and monetary savings.

						adding roof insulation, solar panel installation.	
(McAlister et al., 2023)	Australia	To measure the impact of an intervention to reduce unnecessary testing on pathology collections, associated carbon emissions, and pathology costs.	Retrospective before-and-after study	Secondary	24 585 pathology collections in 5695 patients were identified	The intervention involved limiting non-urgent pathology testing to two days per week (Mondays and Thursdays), with testing on other days only when urgently required. This policy was communicated through department meetings, staff orientations, and posters.	CO_2e saving on tests performed

(Ramírez Franco, Castañeda Cárdenas, & Zea Ramírez, 2023)	Colombia	The present work evaluated the use of ilmenite in its natural state as a photocatalyst for the photocatalytic degradation of dyes present in real clinical laboratory wastewater produced during Gram staining, Ziehl-Neelsen staining, and Wright staining procedures.	Experimental study	Tertiary	Not stated	The intervention involved using ilmenite as a photocatalyst under UV-C light with hydrogen peroxide, optimizing ilmenite loading, particle size, and reuse cycles to achieve over 90% discoloration efficiency in clinical laboratory wastewater treatment.	Quantification of dyes found in laboratory wastewater
(Reid, Kehrer, & Badrick, 2012)	Australia	Implementation of ISO14001 into a clinical pathology setting to see what impacts they would have on improving environmental sustainability.	Retrospective before-and-after study	Private independent laboratory	3 sites, plus one administration unit.	They improved recycling rates, reduced landfill, recycled printer cartridges, Recycled xylene, turned equipment and lighting	Quantification of recycling rates, waste to landfill,

						off, changed how they disposed of stains, introduced rainwater tanks to reduce water consumption, and improved training and engagement. They also reduced paper use, and reduced specimen bag usage, and recycled vacutainer barrels.	

Specific clinical test

Of the 15 studies which assessed the environmental impact of a specific clinical test, 14 were observational studies, and 1 was an intervention study. Of the 14 observational studies, seven studies established environmental impact in a single time period using a cross-sectional (n = 9), life-cycle assessment (n = 2), cohort study (n = 1), observational study (n =1) and case series design (n = 1).

Specific clinical test - Blood specimen tests

Regarding the specific focus of clinical tests, five studies examined the environmental impact of blood sample testing (see table 3 for specific test types for blood specimen tests). For these five studies the environmental outcomes were CO_2e (n = 5) and waste in kgs (n = 1).

Table 3. Study Characteristics of Observational Studies on Specific Clinical Test: Blood specimen

Author	Country of study	Aims of the study	Study type/design	Diagnostic test	Sample size	Environmental outcomes
(Breth-Petersen et al., 2022)	Australia	Assessment of health, financial and environmental impacts of inappropriate vitamin D testing	Mixed (Systematic review & cross-sectional study)	Unnecessary vitamin D testing	4,457,657 Medicare-funded vitamin D tests in 2020	CO_2e (Cost)
(Glover, Booth, & Wiencek, 2023)	USA	Quantifying the amount of recyclable and nonrecyclable biomedical waste produced by performing the complete metabolic panel.	Retrospective cross-sectional study	Complete metabolic panel (CMP)	Not stated	Waste in kg and CO_2e of the recyclable portion of this.
(Gray et al., 2021)	UK	Using the 'sustainability in quality improvement' framework, the study aimed to evaluate the intraoperative usage and financial, environmental and social impacts (the 'triple bottom line') of a G&S prior to laparoscopic/diagnostic appendicectomy	Retrospective service evaluation (cross-sectional data)	Blood group typing	10,196 patients had group and save for potential laparoscopic appendicectomy or emergency laparoscopy	CO_2e
(McAlister, Barratt, &	Australia	To estimate the carbon footprint of five common hospital pathology	Life cycle assessment	Full blood examination, coagulati	Life cycle assessment for each	CO_2e

McGain, 2020)		tests: full blood examination; urea and electrolyte levels; coagulation profile; C-reactive protein concentration; and arterial blood gases.		on profile, U&E, CRP, ABG	individual test	
(Spoyalo et al., 2023)	Canada	Show carbon cost of unnecessary testing in surgery patients	Retrospective cohort study	Unnecessary vitamin D testing. Complete metabolic panel (CMP). Blood group typing. Full blood examination (FBE), coagulation profile, urea plus electrolytes, CRP, arterial blood gas, and urinalysis.	304 patients met inclusion criteria	CO_2e

Specific clinical test - Various Sample Types.

The remaining studies utilized a variety of sample types, including equipment/substance focused (n = 2), gastrointestinal biopsy (n = 1), prostate biopsy (n = 1), nasopharyngeal sample (n = 1), plasma, urine & oral fluid (n = 1), cultures during incision and drainage (n = 1), urine culture & blood (n = 1) and urine culture (n = 1) (See table 4 Study Characteristics of Observational Studies with Various Sample Types). The environmental outcomes assessed included CO_2e (n = 4), laboratory plastic waste measured in kg (n = 1), a score based on a conglomerate of novel, proposed criteria (n = 1), xylene and ethanol (L) (n = 1), energy in KWh (n =1), and weight of disposable plastic components of a test (n = 1). Two studies assessed the cost of equipment and potential cost saving.

Table 4: Study Characteristics of Observational Studies with Various Sample Types.

Author	Country of study	Aims of the study	Study type/design	Sample type	Diagnostic Focus	Sample size	Environmental outcomes
(Farshidpour et al., 2022)	USA	We aimed to estimate the environmental impact of urine cultures and suggest inappropriate culturing as a target for diagnostic stewardship and waste mitigation.	Retrospective cross-sectional study	Urine culture	Urine culture	533 samples	Laboratory plastic waste measured in kg
(Gordon et al., 2021)	USA	We applied life cycle assessment to quantify GHGs associated with processing a gastrointestinal biopsy in order to identify emissions hotspots and guide	Retrospective cross-sectional study	Gastrointestinal biopsy processing	Gastrointestinal biopsy processing	Not stated	CO_2e

		mitigation strategies.					
(Gorynski, Sobczak, & Kolodziej, 2024)	Poland	To develop and evaluating the greenness of a Thin-Film Microextraction protocol for determining fentanyl, methadone, and zolpidem in plasma, urine, and oral fluid	Methodological validation study (cross-sectional data)	Plasma, urine, and oral fluid	Drugs of abuse on plasma, urine & oral fluid	Not stated	A score based on a conglomerate of novel, proposed criteria.
(Huang & Ciesla, 1992)	US	Commercially available, small-scale solvent distillation units were evaluated at two U.S. Army health care facilities to determine whether used xylene, ethanol and citrus-based	Case series	Equipment/substance focused	Histopathology fixation	N/A	Xylene and ethanol (L) (cost of equipment)

		laboratory solvents could be effectively recycled.					
(Leapman et al., 2022).	USA	We aimed to estimate the environmental impact of transrectal ultrasound (TRUS) prostate biopsy, a procedure that is commonly performed in excess of recommended guidelines based on patient age or life-expectancy.	Life cycle assessment	Prostate biopsy	Prostate biopsy	Life cycle assessment of an average prostate biopsy from collection to processing in the laboratory	CO_2e
(Rybinski et al., 2018)	UK	Review use of culture swabs and drainages in patients to identify unnecessary applications. Then do a simple carbon,	Retrospective observational study	Cultures during incision and drainage	Cultures during incision and drainage	206 patients, 176 had cultures sent, 63 had multiple and 102 were positive.	CO_2e (possible total cost saving)

		financial and time assessment to show what the impact of those unnecessary procedures were.					
(Mansuy et al., 2022)	France	The aim was to estimate the amount of plastic used in both molecular and antigenic diagnostic assays for COVID-19.	Retrospective cross-sectional study	Nasopharyngeal sample	Nasopharyngeal sample	362,000 PCR tests in the laboratory, 7,002,012 PCR tests regionally and 7,198,479 antigen tests regionally	Weight of disposable plastic components of a test
(McAlister, Grant, & McGain, 2021)	Australia	The aim of this study is to develop an LCA of six commonly used pathology tests in hospitals in Australia, as testing is ubiquitous within	Retrospective cross-sectional study	Blood and urine samples	Blood and urine samples	LCA for full blood examination (FBE), coagulation profile (APPT or INR), urea plus electrolytes (U+E), CRP,	CO_2e

		healthcare.				Arterial blood gas (ABG) and urinalysis.	
(Ni et al., 2018)	UK	The aim was to determine the CO_2 equivalence of using the Biochrom 30+ amino acid analyser.	Retrospective cross-sectional study	Equipment/substance focused	Environmental impact of the Biochrom 30+ amino acid analyser	One sample in 5 scenarios	CO_2e & energy in KWh

Specific clinical test - Experimental studies

Only one study assessed an intervention for a specific clinical test (See table 5 study characteristics). This intervention focused on adoption of regulatory guidelines. The environmental impact was assessed through the reduction of testing after implementing a new guideline procedure. The environmental assessment focused on the CO_2e and corresponding cost savings.

Table 5: Study characteristics of intervention study for pre-surgery blood typing

Author	Country of study	Aims of the study	Study type/design	Sample type	Diagnostic Focus	Sample size	Intervention
(Siddique & O'Brien, 2023)	UK	Blood transfusion is rarely required for patients undergoing laparoscopic appendicectomies (LA) however some NHS trusts still require group and screen (G&S) sampling. This study aimed to assess	Retrospective before-and-after study	Blood sample for group and save	Pre-surgery blood typing	A retrospective observational study was conducted in our centre from 01/02/2022-01/06/2022 (cycle one) and 20/04/23-20/08/2023 (cycle two	The intervention falls und Behavioural Interventions and Regulato Compliance: Guideline implementatio A guideline w introduced avoid routi G&S sampli for laparoscop

		G&S sampling for LA, rate of transfusion and the cost of G&S sampling at our hospital. It re-assessed these parameters after introduction of a guideline specifying that G&S are not needed routinely and should only be considered in case of high-risk patients (including those with deranged clotting, anticoagulation or profound anaemia).				post, guideline introduction). All patients undergoing emergency LA were included.	appendicector patients.

Discussion

It is evident that there has been some historical scholarly interest in the environmental impact of laboratory testing with the first paper being published 50 years ago. However, more recently this interest has increased with the majority of papers being published within the last 10 years. Despite this growing interest there have been relatively few studies assessing interventions within clinical laboratories through the lens of the environmental impact. All but one of the intervention studies were conducted after 2021. The search dates for this scoping review concluded in early February 2024, hence the small numbers of studies included from that year. It is reasonable to predict that at least a similar number of studies were published in 2024 as in the preceding few years, if not more considering the recent trend is showing increasing publications.

Analysis of geographical location of the studies suggest a preponderance of high-income settings. This highlights the need for further research within low to middle income countries, as there is substantial potential to reduce the environmental impact of clinical laboratories within these regions (Rasheed et al., 2021). However, with individual studies being performed in geographically diverse settings, the environmental impact of clinical laboratories appears to be of scholarly interest in multiple regions around the world. This growing global interest in the environmental impact of laboratory testing may be influenced by international groups and organizations advocating for and promoting sustainable practices (Australian Clinical Labs, 2024; European Federation of Laboratory Medicine, 2023; United States Environmental Protection Agency, 2024).

There was limited connectivity of papers and internal citations which may suggest a lack of coordination within this field. However, this lack of limited connectivity may relate to the heterogeneity within the areas under investigation but could also be suggestive of a paucity of globally diverse papers. Despite this possible moderating factor, it does highlight the need for greater coordination, as coordinated interventions, both individually and at an organisational level, can be more effective in reducing environmental impacts (Alt et al., 2024).

Studies were grouped into two levels: laboratory and clinical test levels, encompassing both observational and interventional studies. At both levels there was notable heterogeneity regarding clinical environment and test type factors for both types of studies. There was some consistency in the observational studies regarding the outcomes assessed, with waste quantified in kilograms, and CO_2e calculated at both the laboratory and clinical test levels.

At the laboratory level, it is vital that future observational studies establish a common outcome set and adopt a systematic categorisation by test type or volume to enable cross-comparison of laboratories of different sizes and types. This research direction would enable a method of establishing the degree of contribution that clinical laboratories are having on the environment by presenting a range of effect. This will also facilitate in establishing benchmarks and goals for future development at this level. A similar lack of consistency in effect may also be observed within the intervention studies at this level due to the wide variation in approaches and interventions implemented. Current work on greater standardisation in assessing the environmental impact of clinical laboratories is being undertaken in England through the development of laboratory networks (NHS England, 2020c). These pathology networks are being assessed for their maturity

against a nationally set list of key performance indicators. Environmental sustainability has now been added to this process, and this may eventually mandate laboratories to consider their impact.

To improve the reliability of the outcomes of such studies, reducing the granularity of assessments may be beneficial. Focusing on single laboratory tests with standardised, repeatable procedures could enhance comparability between laboratories and allow for more reliable estimates of environmental impact. From an interventional perspective, this principle of repeatability would also be evident. The focus of the studies is crucial if the aim is to establish a consistent and repeatable estimate of an effect. The substantial variation within laboratories makes achieving a standardised estimate of effect challenging, particularly from a repeatability perspective. Attempts have been made to estimate the environmental impact of various healthcare systems and processes, including renal care (Connor, Lillywhite, & Cooke, 2010), cataract surgery (Thiel et al., 2017), surgery overall; (Brighton Sussex Medical School, 2023), and healthcare in its entirety (Lenzen et al., 2020). These analyses detail the scale of the environmental impact of these processes in CO_2e via detailed life cycle assessment. This level of detail is required to identify resource-intensive hotspots that could benefit from targeted interventions, as well as establishing a baseline from which improvements can be made.

Whilst this review demonstrates an increasing academic interest in this topic, it is clear that significant further work is required. We propose that the life cycle assessment of commonly performed pathology tests be undertaken with robust, reproducible methodology. This would allow pragmatic comparison of the contribution of the different elements (e.g. patient travel, phlebotomy, specimen transport, laboratory analysis, waste). of the testing pathway to the overall carbon footprint. Research focussed on optimising these stages, with an emphasis on reducing unnecessary work could lead to significant gains.

Limitations of the scoping review

This scoping review has some methodological limitations. Screening and data extraction were conducted by a single reviewer; however, a 10% verification process was implemented for both. Additionally, Copilot was used to double-check all extracted data items. While we consider our search strategy to be robust, we identified three additional studies through hand searching and citation screening, which may indicate potential recall issues. Nonetheless, we do not believe this would substantially alter the overall findings of this scoping review. Furthermore, we included only English-language papers in both the search strategy and screening, which may have introduced geographical bias in the included studies.

Conclusion

Whilst this scoping review demonstrates an increasing interest and awareness in this important field, the diversity of reported outcomes and limited interconnectivity of the studies suggest that this is a still a developing area. The first stage of improving a process is to establish a baseline or starting point from where advancements may be measured. With a lack of consensus in methodologies and outcomes, this baseline analysis of the environmental impact of clinical laboratories seems distant. Future efforts should focus on enhancing the assessment of individual laboratory tests, promoting greater standardisation of methodologies and outcomes, and

repeatability to improve the reliability of environmental impact evaluations. This challenge will also be evident in intervention studies, as the underlying inconsistency would lead to a similar variability in intervention effects. This lack of consistency would make repeatability and standardisation difficult, ultimately preventing long-term improvements and refinements of the intervention based on key moderating factors.

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Supplement file 1:

Appendix 1

Database: Ovid MEDLINE(R) ALL <1946 to February 02, 2024>
Date searched: 05/02/2024

1. Climate Change/
2. Environmental Pollution/
3. Greenhouse Effect/
4. Recycling/
5. Carbon Footprint/
6. Greenhouse Gases/
7. Conservation of Natural Resources/
8. Conservation of Energy Resources/
9. Conservation of Water Resources/
10. Environmental Monitoring/
11. (environmentally friendly or ecological impact* or greenhouse gas* or climate change or carbon footprint or global warming or planetary health or changing climate or climate responsibility or recycling or pollution or life cycle assessment*).ti,ab.
12. (environment* adj6 (sustainab* or impact* or cost* or burden* or wast* or resource* or conserve* or monitor*)).ti,ab.
13. (emission* adj3 (carbon or co2 or methane or CH4 or nitrous oxide or N2O or Hydrofluorocarbons or HFCs or Perfluorocarbons or PFCs or Sulphur hexafluoride or SF6 or Nitrogen trifluoride or NF3)).ti,ab.
14. or/1-13
15. laboratories, hospital/ or pathology department, hospital/
16. Laboratories, Clinical/
17. ((lab or labs or laboratory or laboratories) and (clinical or hospital)).ti,ab.
18. (pathology lab* or hospital pathology or pathology test* or pathology service* or "point of care testing" or "near patient testing").ti,ab.
19. or/15-18
20. 14 and 19
21. exp animals/ not humans.sh.
22. (animal* or rabbit* or rat or rats or mouse or mice or chicken* or dog or dogs or cat or cats or feline or pig* or monke* or fish).tw.
23. 21 or 22
24. 20 not 23
25. limit 24 to english language

Database: Embase (Ovid) <1974 to 2024 February 02>
Date searched: 05/02/2024

1. climate change/
2. pollution/

3. greenhouse effect/
4. recycling/
5. carbon footprint/
6. greenhouse gas/
7. environmental protection/
8. water conservation/
9. energy conservation/
10. environmental monitoring/
11. (environmentally friendly or ecological impact* or greenhouse gas* or climate change or carbon footprint or global warming or planetary health or changing climate or climate responsibility or recycling or pollution or life cycle assessment*).ti,ab.
12. (environment* adj6 (sustainab* or impact* or cost* or burden* or wast* or resource* or conserve* or monitor*)).ti,ab.
13. (emission* adj3 (carbon or co2 or methane or CH4 or nitrous oxide or N2O or Hydrofluorocarbons or HFCs or Perfluorocarbons or PFCs or Sulphur hexafluoride or SF6 or Nitrogen trifluoride or NF3)).ti,ab.
14. or/1-13
15. hospital laboratory/
16. clinical laboratory/
17. ((lab or labs or laboratory or laboratories) and (clinical or hospital)).ti,ab.
18. (pathology lab* or hospital pathology or pathology test* or pathology service* or "point of care testing" or "near patient testing").ti,ab.
19. or/15-18
20. 14 and 19
21. Animal experiment/ not (human experiment/ or human/)
22. (animal* or rabbit* or rat or rats or mouse or mice or chicken* or dog or dogs or cat or cats or feline or pig* or monke* or fish).tw.
23. 21 or 22
24. 20 not 23
25. limit 24 to english language

Database: Environment Complete (EBSCOhost)
Date searched: 05/02/2024

S1. DE "CLIMATE change"
S2. DE "POLLUTION"
S3. DE "GREENHOUSE effect" OR DE "GREENHOUSE gases"
S4. DE "WASTE recycling"
S5. DE "ECOLOGICAL impact"
S6. ((DE "CONSERVATION of natural resources") OR (DE "CONSERVATION of energy")) OR (DE "WATER conservation")
S7. TI ("environmentally friendly" or "ecological impact*" or "greenhouse gas*" or "climate change" or "carbon footprint" or "global warming" or "planetary health" or "changing climate" or "climate responsibility" or recycling or pollution or "life cycle assessment*") OR AB ("environmentally friendly" or "ecological impact*" or "greenhouse gas*" or

"climate change" or "carbon footprint" or "global warming" or "planetary health" or "changing climate" or "climate responsibility" or recycling or pollution or "life cycle assessment*")

S8. TI (environment* N6 (sustainab* or impact* or cost* or burden* or wast* or resource* or conserve* or monitor*)) OR AB (environment* N6 (sustainab* or impact* or cost* or burden* or wast* or resource* or conserve* or monitor*))

S9. TI (emission* N3 (carbon or co2 or methane or CH4 or "nitrous oxide" or N2O or Hydrofluorocarbons or HFCs or Perfluorocarbons or PFCs or "Sulphur hexafluoride" or SF6 or "Nitrogen trifluoride" or NF3)) OR AB (emission* N3 (carbon or co2 or methane or CH4 or "nitrous oxide" or N2O or Hydrofluorocarbons or HFCs or Perfluorocarbons or PFCs or "Sulphur hexafluoride" or SF6 or "Nitrogen trifluoride" or NF3))

S10. S1 OR S2 OR S3 OR S4 OR S5 OR S6 OR S7 OR S8 OR S9

S11. TI ((lab or labs or laboratory or laboratories) and (clinical or hospital)) OR AB ((lab or labs or laboratory or laboratories) and (clinical or hospital)) OR KW ((lab or labs or laboratory or laboratories) and (clinical or hospital))

S12. TI ("pathology lab*" or "hospital pathology" or "pathology test*" or "pathology service*" or "point of care testing" or "near patient testing") OR AB ("pathology lab*" or "hospital pathology" or "pathology test*" or "pathology service*" or "point of care testing" or "near patient testing") OR KW ("pathology lab*" or "hospital pathology" or "pathology test*" or "pathology service*" or "point of care testing" or "near patient testing")

S13. S11 OR S12

S14. S10 AND S13

S15. S10 AND S13

Database: Web of Science (Science Citation Index Expanded (SCI-EXPANDED)--1970-present; Social Sciences Citation Index (SSCI)--1970-present; Arts & Humanities Citation Index (AHCI)--1975-present; Conference Proceedings Citation Index-Science (CPCI-S)--1990-present; Conference Proceedings Citation Index-Social Science & Humanities (CPCI-SSH)--1990-present; Emerging Sources Index (ESCI)--2015-present)
Date searched: 05/02/2024

1. TS=("environmentally friendly" or "ecological impact*" or "greenhouse gas*" or "climate change" or "carbon footprint" or "global warming" or "planetary health" or "changing climate" or "climate responsibility" or recycling or pollution or "life cycle assessment*")
2. TS=(environment* NEAR/6 (sustainab* or impact* or cost* or burden* or wast* or resource* or conserve* or monitor*))
3. TS=(emission* NEAR/3 (carbon or co2 or methane or CH4 or "nitrous oxide" or N2O or Hydrofluorocarbons or HFCs or Perfluorocarbons or PFCs or "Sulphur hexafluoride" or SF6 or "Nitrogen trifluoride" or NF3))
4. #1 OR #2 OR #3
5. TS=((lab or labs or laboratory or laboratories) and (clinical or hospital))
6. TS=("pathology lab*" or "hospital pathology" or "pathology test*" or "pathology service*" or "point of care testing" or "near patient testing")

7. #5 OR #6
8. #4 AND #7
9. Limit #8 to English Language