REVIEW

Revisiting the Environmental Impact of Inappropriate Clinical Laboratory Testing: A Comprehensive Overview of Sustainability, Economic, and Quality of Care Outcomes

Luigi Devis [a], Mélanie Closset,[a] Jonathan Degosserie,[b,c] Sarah Lessire,[c,d,e,f] Pauline Modrie,[g,h] Damien Gruson,[i] Emmanuel J. Favaloro [j,k,l], Giuseppe Lippi [m], François Mullier,[c,e,f,n,*] and Emilie Catry[a]

Background: The use of laboratory resources has seen a substantial increase in recent years, driven by automation and emerging technologies. However, inappropriate use of laboratory testing, encompassing both overuse and underuse, poses significant challenges.

Content: This review explores the complex interplay between patient safety, economic, and environmental factors—known as the "triple bottom line" or "3Ps" for people, profit, and planet—associated with inappropriate use of laboratory resources. The first part of the review outlines the impact of inappropriate laboratory testing on patient safety and economic outcomes. Then the review examines the available literature on the environmental impact of laboratory activities. Several practical solutions for mitigating the environmental impact of laboratories are discussed. Finally, this review emphasizes how decreasing unnecessary laboratory testing results in cost savings and environmental benefits, as evidenced by interventional studies, without compromising patient safety.

Summary: The implementation of sustainable practices in laboratories can create a virtuous circle in which reduced testing enhances cost-efficiency, reduces the environmental footprint, and ensures patient safety, thereby benefiting the 3Ps. This review highlights the critical need for appropriate laboratory resource utilization in achieving sustainability in healthcare.

[a]Department of Laboratory Medicine, Biochemistry, CHU UCL Namur, UCLouvain, Yvoir, Belgium; [b]Department of Laboratory Medicine, Molecular Biology, CHU UCL Namur, UCLouvain, Yvoir, Belgium; [c]Namur Research Institute for Life Sciences, Université de Namur, CHU UCL Namur, Namur, Belgium; [d]Blood Transfusion Center, CHU UCL Namur, UCLouvain, Yvoir, Belgium; [e]Namur Thrombosis and Hemostasis Center, CHU UCL Namur, UCLouvain, Yvoir, Belgium; [f]Institute of Experimental and Clinical Research, UCLouvain, Brussels, Belgium; [g]Sustainability Consultant, CHU UCL Namur, UCLouvain, Yvoir, Belgium; [h]Institute of Health and Society, UCLouvain, Brussels, Belgium; [i]Department of Clinical Biochemistry, Cliniques Universitaires St-Luc, UCLouvain, Brussels, Belgium; [j]Department of Haematology, Centres for Thrombosis and Haemostasis, Institute of Clinical Pathology and Medical Research, NSW Health Pathology, Westmead Hospital, Westmead, New South Wales, Australia; [k]School of Dentistry and Medical Sciences, Faculty of Science and Health, Charles Sturt University, Wagga Wagga, New South Wales, Australia; [l]School of Medical Sciences, Faculty of Medicine and Health, University of Sydney, Westmead Hospital, Westmead, New South Wales, Australia; [m]Section of Clinical Biochemistry, University of Verona, Verona, Italy; [n]Department of Laboratory Medicine, Hematology, CHU UCL Namur, UCLouvain, Belgium.

*Address correspondence to this author at: Laboratoire de Biologie clinique, CHU UCL Namur, avenue Docteur G. Therasse 1, 5530 Yvoir, Belgium. Tel +32 81 42 49 86; E-mail francois.mullier@chuuclnamur.uclouvain.be.

Previous Presentation: Parts of this manuscript have been presented as a poster at the annual meeting of the Royal Belgian Society of Laboratory Medicine (2023) and during an oral presentation at the annual meeting of the Namur Thrombosis and Haemostasis Center (2024).

Received April 21, 2024; accepted June 11, 2024.

https://doi.org/10.1093/jalm/jfae087

IMPACT STATEMENT

There is evidence of inappropriate use of laboratory resources, which produces unwanted medical, financial, and environmental impacts. These impacts are intricately intertwined and accumulate to form a vicious circle. However, there is currently no comprehensive overview of the interconnected impacts of inappropriate laboratory testing. Our review highlights the complex ramifications of inappropriate laboratory resource utilization. We highlight how sustainable laboratory practices can mitigate these consequences, fostering cost-efficiency, environmental stewardship, and patient safety. We provide practical solutions to mitigate the environmental impact of clinical laboratories.

INTRODUCTION

The use of laboratory resources has considerably increased in recent years, mainly due to the advent of automation and emerging technologies (1, 2). Laboratory testing has been deployed for a range of purposes, such as screening, diagnosis, therapeutic drug monitoring, prognostication, and more (3). With healthcare professionals increasingly relying on clinical laboratory interventions, laboratory medicine has become an essential tool in healthcare (4, 5).

Laboratory medicine can be susceptible to inappropriate usage, encompassing both overuse (a test that should not be ordered is performed) and underuse (a test that should be performed is not ordered). While the exact extent of inappropriate usage is difficult to determine (6), the estimates suggest that overuse and underuse occurs in 20% and 40% of cases, respectively (7). Additionally, a significant proportion of routine tests performed in high-throughput laboratories may be requested for questionable clinical significance. This concerns around 60% of coagulation tests and around 70% of biochemistry tests (8). Current economic constraints, a growing emphasis on the added value of laboratory medicine and quality of care, as well as the increased awareness of healthcare's environmental impact have led to an increased focus on this issue (9–13).

The consequences of inappropriate laboratory testing can be divided into 3 major categories: patient safety, financial implications, and environmental impact. In the literature, these categories are frequently referred to as the "triple bottom line" or "3Ps," which stands for People, Profit, and Planet. Due to their interdependence, it is often difficult to distinguish between them. For example, an inappropriate laboratory test can result in an unexpected positive result or incidental finding, which may necessitate follow-up tests or interventions. Such actions can increase costs and environmental impact, as well as anxiety and inconvenience for the patient.

This review highlights the intricate interplay between the 3Ps in addressing first the primary impacts of inappropriate testing on patient safety and economic outcomes. Subsequently, this review reports the environmental repercussions of clinical laboratory operations and outlines practical solutions to facilitate a shift toward a more sustainable (i.e., "green") laboratory. Finally, this review shows how environmental, economic, and patient safety outcomes support each other in a "virtuous circle" when actions aimed at reducing them are implemented.

THE VICIOUS CIRCLE OF INAPPROPRIATE LABORATORY TESTING

Inappropriate use of laboratory testing may have adverse outcomes that can compound each other, leading to a vicious circle (Fig. 1). Owing to excessive usage, recurrent phlebotomy may result in

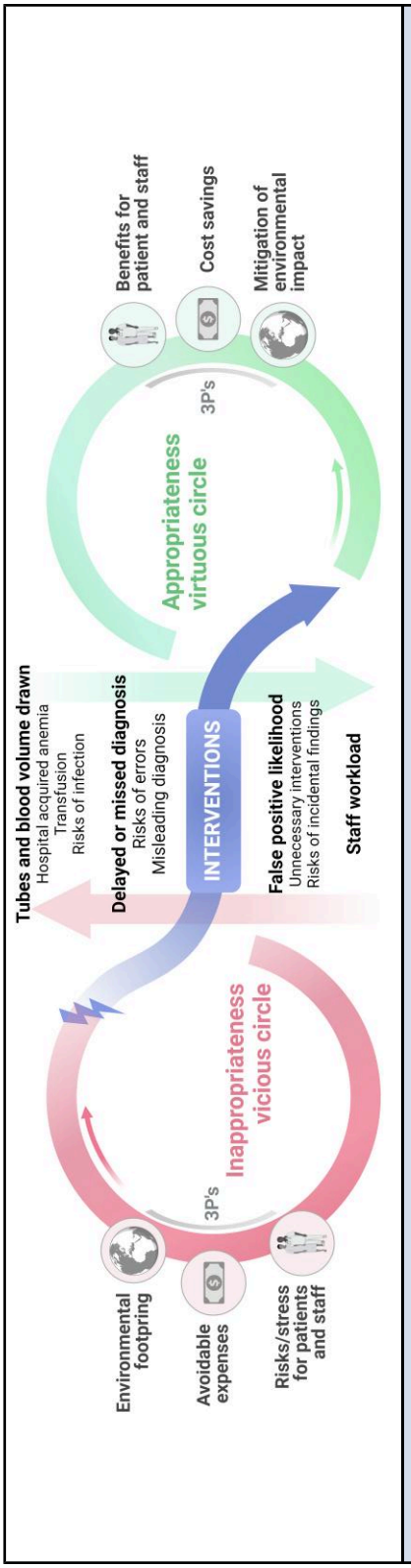

Fig. 1. The vicious (left side) and virtuous (right side) circles of laboratory utilization. Inappropriate use increases costs, environmental impact, and workload for staff and results in poorer quality of care for patients, forming a vicious loop. Well-conducted stewardship interventions can reverse this circle, reducing inappropriate tests, saving costs, and lessening environmental impact while maintaining patient safety. Created with BioRender.com.

hospital-acquired (or iatrogenic) anemia, which is associated with increased mortality and prolonged length of stay (14–16). In the intensive care unit (ICU), a simulation integrating a clinical context of reduced erythropoiesis, lower limit of initial hemoglobin concentration (110 g/L), low body weight, and increased phlebotomy showed that the transfusion threshold for hemoglobin (around 70 g/L) can be reached within only 9 to 14 days of admission (17). The need for transfusion translates into its own risks, side effects, and increased costs (18, 19). Particularly, excessive collection of blood samples can be detrimental for frail patients, such as neonates and children, who are highly susceptible to changes in blood volume (20). Moreover, the overuse of laboratory tests burdens phlebotomy and laboratory staff, thus increasing the risk of errors, enhancing the overall costs and waste; causes patient discomfort and stress; increases the risk of nosocomial infections; and yields incidental findings (i.e., "laboratory incidentalomas") that may lead to further unnecessary tests or interventions and may result in diagnostic errors and inappropriate therapeutic choices (7, 8, 15, 16, 21–26).

Conversely, it is important to consider the long-term advantages of testing. A test that can prevent potential complications and the subsequent requirement for further diagnostic investigations, interventions, or treatments should be regarded as valuable and appropriate (27). For example, an Argentinian study showed that the implementation of a procalcitonin-guided algorithm resulted in 734 500 fewer antibiotic treatment days, 7900 fewer antibiotic-resistance cases, and 5100 *C. difficile* infection cases avoided, resulting in potential annual savings of US$83 million for the Argentinian healthcare system (28). Underuse of such tests can also lead to missed or delayed diagnosis and compromise patient safety. For example, a study (29) found that malpractice claims in the ambulatory setting were caused by failure to order an appropriate diagnostic test (imaging and laboratory) or its incorrect interpretation in 55% and 37% of

cases, respectively. Overall, 59% of the cases resulted in serious harm for the patient and 30% in death. More recently, Cadamuro et al. (30) retrospectively analyzed the records of 2244 patients with microcytic anemia and showed that 40% of patients were not appropriately followed up, leading to potential incorrect or absent treatment or missed diagnosis (e.g., thalassemia). A large meta-analysis estimated that underuse is about twice as frequent as overuse (7). However, underuse is less represented in the literature (31), perhaps because its consequences are more challenging to assess than its counterpart overuse (30).

Lastly, improper use of laboratory resources also has economic consequences (32). For example, a 1536-bed university hospital in Italy calculated avoidable expenses of €86 000 monthly due to unnecessary examinations (33). Similarly, in a study conducted in Canada, redundant repetition tests in adults were found to cost an estimated CAN$13.9 to 35.9 million yearly (34).

Altogether, these data indicate that inappropriate laboratory testing, encompassing both over- and underuse, is frequent and results in potential patient harm, lower quality of care, greater workload on staff, and increased economic impact. However, another impact of inappropriate laboratory use that has received less attention is the environmental impact of unnecessary testing.

THE ENVIRONMENTAL IMPACT OF LABORATORY MEDICINE

Climate change has a significant impact on health and is considered as one of the "biggest global health threats" of the 21st century (35). However, it is paradoxical that the healthcare sector is a significant contributor to global warming. Greenhouse gas (GHGs) emissions from the healthcare sector constitute 3% to 10% of total national emissions, depending on the country of reference (36–41). At the Organization for Economic Cooperation and Development level, these emissions are similar to those generated by the food sector (41).

Inappropriate Laboratory Use Contributes to the Global Healthcare Footprint and Raises Costs

The extent of laboratory medicine's role in the global environmental impact of healthcare system is not precisely known (42). Nevertheless, several recent studies have provided an estimate. A survey of the environmental impact of Australia's largest health service revealed that pathology and diagnostic services are responsible for 12% of water usage, 8% of waste production, and 9% of carbon dioxide equivalent (CO_2e) emissions (43). Additionally, there are indications that inappropriate laboratory testing results in significant GHG emissions. McAlister et al. (44) estimated the amount of CO_2e produced by some laboratory tests performed regularly [full blood count, coagulation screening (activated partial thromboplastin time and international normalized ratio), electrolytes (sodium, potassium, chloride, calcium, phosphate) and urea, C-reactive protein, and arterial blood gas]. Using an International Organization for Standardization (ISO) 14040-compliant life cycle assessment (LCA) method (see later discussion), the authors estimated that a full blood count was responsible for emitting 116 g CO_2e, corresponding to a 770 m drive in a standard car (44). At the CHU UCL Namur (936-bed Belgian academic center), an average of 620 full blood counts are performed daily, and similar usage is evidenced in other centers. Owing to McAlister et al.'s estimations—and if the Australian estimates correspond to the Belgian situation (see later discussion)—this represents a 477-km commute each day only for this one test. When combining the 5 panels of tests discussed in McAlister et al.'s study, the 936-bed facility has generated a total distance of 359 705 km traveled by car in the year 2022. This is equivalent to 9 times the earth's circumference (Fig. 2). Recently, Spoyalo et al. (45) conducted an evaluation of laboratory testing inappropriateness in the acute care

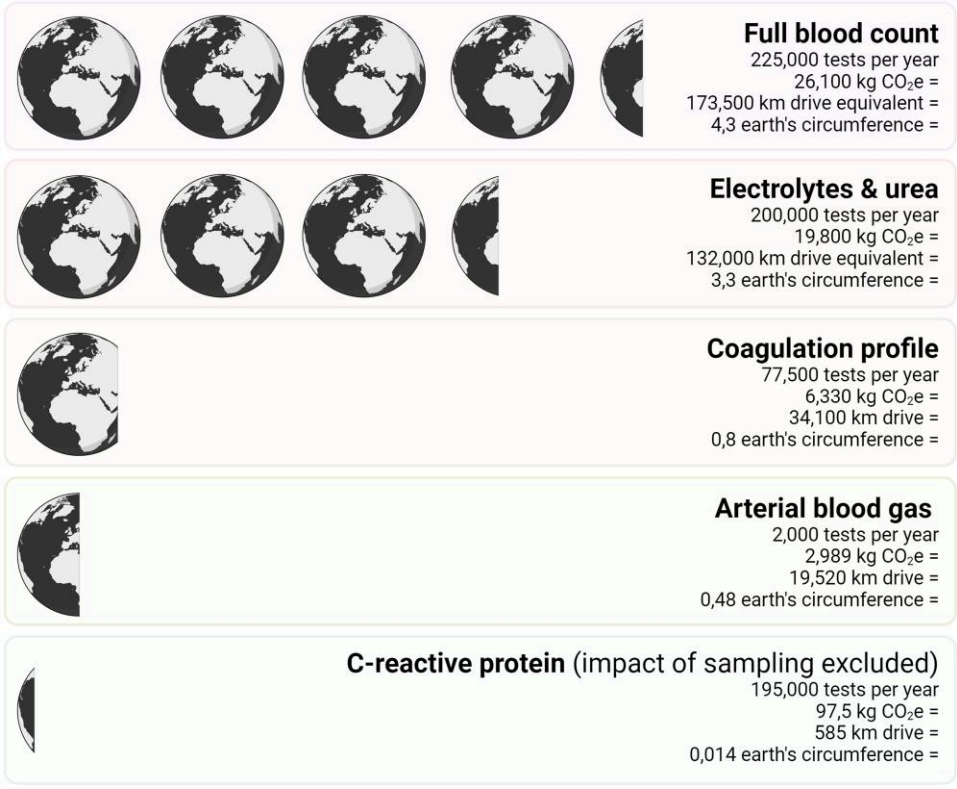

Fig. 2. Annual CO_2e emissions of 5 routine pathology tests performed in CHU UCL Namur (1000-bed hospital). Estimates are given in kilometers driven by a standard car and corresponding equivalent in terms of earth's circumference (40 000 km), using estimations from McAlister et al. (44). Electrolytes and urea: blood urea nitrogen, sodium, potassium, chloride, calcium, magnesium, phosphate. Coagulation profile: activated partial thromboplastin time and international normalized ratio. Created with BioRender.com.

surgical setting of a 700-bed hospital over a 1-year period (n = 304 patients included). Their analysis suggested that 76% of the tests performed were inappropriate, resulting in unnecessary emissions of 112 kg CO_2e. The annual cost savings for the 21 selected tests would have amounted to CAN$10 000. Another Australian study (46) evaluated the impact of inappropriate vitamin D prescription nationwide over the year 2020. The study estimated that 76.5% of tests were ordered with no net health benefit, resulting in 3 410 000 inappropriate tests that cost Medicare AUS$87 million. In addition to the financial costs, the vitamin D testing also emitted between 28 000 and 42 000 kg CO2e for the plastic and energy used to run the tests (i.e., no assessment of the "cascade" impacts).

Single-Use Consumables Are Responsible for the Greatest Proportion of Laboratory Environmental Footprint

Currently, it is estimated that the most environmentally damaging aspect of laboratory testing is its use of consumables (44). Among the consumables used in clinical laboratories, those associated with specimen collection (i.e., needle holder and collection tube, nitrile gloves and swabs, and ziploc bags) have the greatest environmental impact, estimated at approximately 50% for this phase alone

(44, 45). It appears that the environmental impact of these items is mainly due to their single-use nature rather than to the materials from which they are made. Farley et al. (42) conducted a comparison between disposable plastic materials and reusable glass materials in a basic research laboratory setting. The study focused on petri dishes, Pasteur pipettes, conical cubes, and conical culture flasks. The results showed that reusing glass materials has a lower carbon footprint than using single-use plastic materials, despite the higher energy consumption that is required for cleaning, washing, and drying reusable consumables. This study evaluated a basic research facility, which differs from a clinical laboratory in several aspects. The literature lacks data on the environmental impact of clinical laboratory activities. Therefore, it is crucial to gather such data to gain a better understanding of the issue, make evidence-based decisions, and monitor changes more effectively. However, these results align with estimations for clinical facilities, which suggest that sampling materials are the primary contributors to the environmental impact of clinical laboratories (44).

Precise Evaluation of the Environmental Impact of Clinical Laboratories Is Challenging

Assessing and monitoring the environmental impact of clinical laboratories is a multifaceted task. Potential indicators to observe include CO_2e and GHG emissions (often used interchangeably in studies, which add to the complexity), water and air pollution, and the volume of plastic waste generated. However, generalization of results is challenged by the lack of standardization between indicators used in different studies. Multiple methods for assessing the environmental impact of a given component exist. The most commonly utilized approach is the LCA method (47). The LCA method is based on the ISO14040:2006 international standard (48). Briefly, the method evaluates the life cycle of a given functional unit throughout 6 major steps (Fig. 3). An important aspect of LCA is that it assesses the environmental impact of a functional rather than a physical unit, thus making it possible, for example, to calculate the carbon impact of procedures and not solely objects (48). Another important aspect to consider is evaluating the entire life cycle of a product, rather than analyzing it at a single point in time. However, it is important to set arbitrary limits on this life cycle. This is because cycles are self-perpetuating. For instance, the energy needed to produce one functional unit often comes from another functional unit, which would also need to be evaluated, and so on. Additionally, some functional units may have subsequent cycles, such as through recycling. These limitations are called boundaries, within which LCA operates (48). It includes items that will be part of the analysis and excludes those that will not be considered. For example, the LCA of pathology testing conducted by McAlister et al. (44) included ore, agricultural, and oil and gas production but excluded mining, agriculture, and oil and gas infrastructures in their system boundary. It is reasonable to assume that each different boundary system can lead to varying conclusions about the environmental impact of a functional unit. Another

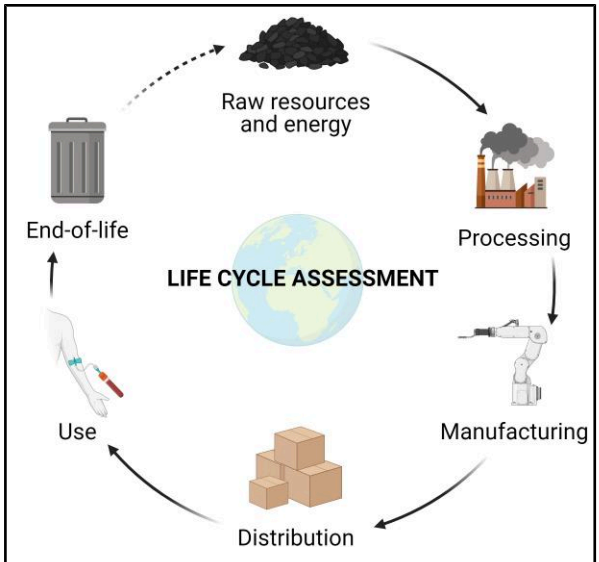

Fig. 3. Schematic representation of the 6 main steps of a LCA method. Created with BioRender.com.

complexity is that the LCA is based on components that may vary from one country to another. For example, energy consumption may vary between 2 countries, depending on which energy is most abundant in each respective country.

Moreover, the choice of the indicator is crucial. An intervention may improve one indicator while worsening another. Failure to choose the right indicators may result in a misleading conclusion that there has been an improvement in environmental impact when, in fact, there has been a deterioration at another level. For example, the use of reusable laboratory materials may reduce energy consumption and waste, but it may also lead to increased wastewater due to the cleaning process. Therefore, focusing solely on 1 indicator should be avoided as much as possible. Tools and standards outlined in the following section can assist in navigating through these complexities.

The complexity of the causal chain of operations involved (i.e., "cascade" impacts) also contributes to the difficulty of evaluation (44). The impact of a laboratory test conducted in 2 different labs with the same reagent may differ. Indeed, much of the environmental impact of testing is the logistics of transporting dilute reagents from one country or site to another. This impact will then vary depending on whether the reagent was imported from a distant country or purchased from a local manufacturer. Moreover, assessing downstream consequences such as waste management and air or water pollution is challenging. Therefore, environmental impact estimations of laboratory testing are limited and could be undervalued.

Finally, it is sometimes difficult to distinguish the environmental impact of a particular test without assessing the influence of the sampling procedure. Indeed, one may question whether removing a laboratory test from a blood sample significantly alters the overall environmental impact, considering that the same equipment (e.g., sampling consumables) will be used regardless. For example, McAlister et al. (44) found that the environmental impact of C-reactive protein, excluding the impact of the sampling procedure, was 100 times less than that of other chemistry and hematology tests. Currently, there is insufficient data to provide a definite answer to this question. Nonetheless, due to the widespread use of laboratory tests globally, even a small reduction in their use could have a significant positive impact on the environment. Additional research is necessary to fully address this issue.

SOLUTIONS FOR THE MITIGATION OF LABORATORIES' ENVIRONMENTAL IMPACT

Inappropriate, Low-Value Care Can Be Managed

Low-value or inappropriate care is a significant cause of both financial and resource waste (9). The World Health Organization has identified appropriateness of care as a crucial principle in developing low-carbon healthcare systems (45). To date, efforts to assess the impact of measures to reduce the environmental impact of healthcare have focused mainly on volatile anesthetics [e.g., fluorinated gases (49)] emitted during surgery (50). For clinical laboratories, we mentioned that the most efficient way to reduce the environmental footprint is to reduce the number of tests prescribed or performed (44). There is significant literature on interventions aimed at reducing inappropriate laboratory testing. Nonetheless, there are few published examples assessing the impact of this reduction on environmental outcomes (Table 1).

Multimodality blood conservation strategies can be implemented to reduce iatrogenic anemia in the ICU setting. These include outside behavioral modifications to reduce test ordering, the use of point-of-care testing (such as arterial blood gas, which consumes less blood than conventional tubes to measure hemoglobin levels and electrolytes), the use of closed blood sampling systems, and the use of small-volume collection tubes to reduce diagnostic blood loss (53). The STRATUS

Table 1. Summary of data from 2 interventional studies assessing the effect of reducing inappropriate laboratory testing on environmental outcomes.

Study (ref.)	Year	Study type	Setting	Intervention	Period	Rationale	Tests selected	Tests ordering impact	Economic impact	Environmental impact
Regan et al. (51)	2018	Prospective quality improvement study	Pediatric cardiology ward (26-bed)	Education: posters and stickers on indications for testing; Audit and feedback: interview of to examine prescription behavior followed by a discussion on indications for testing; communication of preliminary results	15-month preintervention; 32-month postintervention	To reduce the number of combined biochemical tests ordered in neonate patients	Biochemistry tests	13.5% decrease	£11 338 saved (32-month)	17 800 kg CO_2e avoided (32-month)
McAlister et al. (52)	2023	Retrospective cohort study	Department of Medicine from a 653-bed hospital	Gatekeeping: policy to limit nonurgent pathology testing to 2 days per week	6-month preintervention; 6-month postintervention	To evaluate the impact of a stewardship intervention on financial, environmental, and patient safety outcomes	Full blood count, coagulation profile (activated partial thromboplastin time, international normalized ratio), urea, electrolytes, creatinine, C-reactive protein, calcium, magnesium, phosphate, liver function tests	10% decrease	Savings at Department of Medicine scale (per year): AUS$ 53 573; Estimated savings at full hospital activity scale (per year): AUS$500 000 Estimated savings a national scale (per year): AUS$56 million	Department of Medicine scale (per year): 132 kg CO_2e avoided; Full hospital activity scale (per year): 1300 kg CO_2e avoided; National scale (per year): 135 000 kg CO_2e avoided

randomized clinical trial (54), a recent Canadian study, analyzed the transition from standard-volume to small-volume tubes for blood collection in 25 adult medical-surgical ICUs. The study only included patients who had been in the ICU for more than 48 hours. The results showed that the transition to small-volume tubes did not affect laboratory analysis. Additionally, the study found a reduction in red blood cell transfusions in ICU patients, particularly those admitted during the early coronavirus disease 2019 pandemic (as shown in the prespecified secondary analysis). Although the effect of reducing hospital-acquired anemia with small-volume tubes has mainly been studied and observed in ICU patients, their use can be extended to other healthcare units. This has been demonstrated in a 304-bed tertiary care teaching hospital in Florida (55). The utilization of small-volume tubes instead of standard-sized tubes resulted in a significant reduction of diagnostic blood loss for routine testing (hematology, basic metabolic panel, and coagulation testing) by 25%. This approach also led to a decrease in the number of transfusions across units and to an increase in mean hemoglobin levels, particularly in transplant and critical care units. Furthermore, there was no increase in the number of redraws for diagnostic testing. Assessing the potential reduction in carbon footprint in the life-cycle assessment of small-volume tubes compared to standardized collection tubes, especially at a large scale, would be of interest.

Practical Solutions for Reducing the Environmental Impact of Laboratories

There are numerous practical solutions proposed for mitigating the environmental impact of laboratories (56–67). An overview of frequently cited solutions is provided in Table 2. The appointment of a laboratory environmental manager and implementation of an environmental management system (EMS) are crucial steps toward promoting a more sustainable laboratory. International guidance, such as the "ISO 14000 family" (56) of standards, should be applied for environmental management, and regular reviews in the form of "sustainability audits" are required to monitor progress toward these standards. Education of both laboratory staff regarding the environmental impact of laboratories and healthcare professionals regarding the appropriateness of laboratory testing is crucial for mitigating the environmental impact of laboratory medicine. The implementation of stewardship interventions may be a viable solution. These interventions can employ multiple strategies to reduce the inappropriate use of laboratory tests. Two studies were found that specifically estimated the amount of CO_{2e} that could be avoided by reducing inappropriate laboratory testing (Table 1). Regular assessments of equipment, reagents, chemicals, and furniture usage should be carried out prior to any purchase through the implementation of a "sustainable procurement policy" (sometimes referred to as "green purchasing policy"). Despite certain challenges (57), there are existing frameworks for incorporating LCA in health technology assessments (48). Particular attention should be given to the transportation of both samples and laboratory staff. The implementation of smaller and/or more environmentally friendly vehicles, or even innovative transportation methods [e.g., drones (58, 59)], should be explored. Several strategies to conserve energy and water have been suggested, which include the use of light-emitting diodes, fostering a "switching off" and "think twice" culture, regularly assessing water management, incorporating a rainwater collection system for nonpotable water use, and utilizing low-consumption or waterless sanitary facilities. Although possibilities for reusing and recycling waste in medical laboratories are increasing (60), limitations still persist due to concerns around biosafety and cross-contamination risks. Therefore, the immediate priority should be focused on reducing waste (44), which ultimately results in the reduction of consumption. Waste management should also be regularly reviewed to ensure the laboratory reuses or recycles as much as possible (61). Tools provided by nonprofit, national, or

Table 2. Common proposed actions in the literature to mitigate environmental impact of laboratories (61–63, 65, 67–74).

Education and stewardship solutions
• Raise awareness on laboratory's environmental impact (70, 71)
• Provide training for laboratory staff (70, 73, 74)
• Educate about appropriate laboratory tests' request and promote interventions to reduce inappropriate laboratory testing (63)
• Reduce sampling volume and collection tubes used (67)
Material solutions
• Remove chemicals wherever possible and utilize green chemistry to be replaced with less toxic alternatives (61, 73)
• Track the chemical inventory to avoid overpurchasing (73)
• Adopt a green purchasing policy for material and reagents (energy-efficient equipment; local reagents to reduce transport impact, reduce or recycle packaging, etc.) (61, 71)
• Save paper and/or use recycled paper (61, 63, 67, 70–72)
• Purchase environmentally friendly furniture (71, 72)
• Remove vacuum aspirators and replace them with vacuum pumps (61)
• Use alternatives for sample transportation (hybrid or electric vehicles, bicycles, small cars, drones, etc.) (61, 63, 71)
• Utilize reusable material and recycle whenever possible (62, 68–71)
• Batch tests (62)
• Share unused kits or equipment when possible (61, 67, 72, 73)
Energy and water-saving solutions
• Use renewable energy when possible (61, 62, 67, 69)
• Use light-emitting diodes and sensors, and use natural light as much as possible for lighting (61–63, 71, 72)
• Install a "switch-off" culture (lights, computers, nonessential equipment, etc.) and ensure sleep mode on devices, e.g., by conducting an "end of day" walkthrough daily (61, 69–72)
• Install a "think twice" culture (emails, printed papers, etc.) (61, 70)
• Shut down the sash on fume hoods when not in use (61, 63, 71)
• Adopt regular assessment of freezers content and defrost freezers on a regular basis (63)
• Ensure windows and doors are closed when using air conditioning (61)
• Set thermostat to a reasonable level according to the season (70)
• Reuse warmth from equipment during winter (62)
• Use low-consumption or waterless toilets and urinals (62, 72)
• Use rainwater as a source for nonpotable water use
• Use timers for water use and check for faucet leaks (61)
• Monitor the management of water chemistry (61)
• Run autoclaves at full capacity (61)
• Use chiller bath instead of continuous water flow (72)
Organizational solutions
• Appoint a laboratory environmental manager (71,73)
• Adopt an environmental management strategy and indicators of sustainability (61, 63, 67, 70–73)
• Follow international recommendations such as ISO14001:2015 (63, 71)
• Use organizational tools or resources such as GES 1point5 tool or Laboratory Efficiency Assessment Framework (63)
• Promote "sustainability audits" to monitor impact and progress of policies (70–73)
• Provide feedback to employees (73)
• Centralize testing for nonurgent tests (63)
• Use LEED-accredited architects for new buildings or renovations (71, 72)
• Encourage car-pooling or alternative transportation for staff (62, 71)
• Promote innovation and initiative (67, 73)
Technological solutions
• Use artificial intelligence wisely (63)
• Use drones to transport samples (as listed before) (61, 63)

international organizations and societies can aid in this effort (see later discussion). Another solution is to batch tests, or to centralize nonurgent, routinely prescribed tests in a central laboratory ("hub") (62, 63). Consolidation of low-volume testing performed in smaller laboratories into high-throughput facilities represents a significant opportunity for savings—both economic and environmental—that extend beyond the purchase of equipment to include reagents, controls, and calibrators (63).

Point-of-care testing is also mentioned as a solution to reduce the environmental impact of laboratory testing, but views on this topic are controversial. While point-of-care testing could eliminate sample transport, it is still hampered by issues of analytical quality, throughput, and cost and represents a significant source of unsustainable plastic consumption (64). Technological advancements could play a future role in laboratories, for example by using artificial intelligence algorithms to optimize laboratory processes and reduce inappropriate utilization of resources or by expanding the use of telemedicine devices (61, 63, 65–67). An evaluation of "environmental effectiveness" and ethical aspects of such technologies would be necessary to ensure their efficiency and reasonable utilization (75–77). Clinical decision support systems can also be used in integration with computerized physician order entry and laboratory information systems (78). These systems can generate alerts for clinicians regarding guidelines for testing, appropriate retesting intervals, or redundancy of prescribed tests. Integrated with electronic health records, these types of software could provide useful information on the appropriateness of a test in each clinical context (79).

Organizational Standards and Tools to Support Healthcare Transition

Numerous international or national organizations offer valuable educational materials, tools, and guidance to reduce the environmental footprint of laboratories. The ISO offers the "ISO 14000 family" standards for EMS development and implementation (56). The Sustainable Healthcare Coalition in the UK provides valuable data and expert guidance "to inspire sustainable practices" within the healthcare sector (80). The University College London has developed the Laboratory Efficiency Assessment Framework, which includes helpful tools, calculators, and resources, with the aim of improving the sustainability and efficiency of laboratories (81). My Green Lab, a nonprofit organization, provides educational resources, certification for green labs, and the ACT® Environmental Impact Factor label (82). International scientific societies have task forces to address the transition to green laboratories, such as the International Federation of Clinical Chemistry and Laboratory Medicine Task Force Environmental Impact of Laboratory Medicine (83) or its European counterpart (EFLM) Task Force: Green and Sustainable Laboratories (84), that has produced valuable resources including an EFLM Guidelines for Green and Sustainable Medical Laboratories (61).

There are several other strategies to help control inappropriate test utilization, including the various worldwide "choosing wisely" campaigns to educate on wise choices for pathology testing (85). This initiative began in 2012 with 9 national specialty societies (representing 375 000 clinicians) offering 45 examples of tests or treatments that were commonly used in their fields but lacked strong supporting evidence. Between 2012 and 2023, more than 80 specialty societies highlighted additional examples (86). Several recommendations appear in various "choose wisely" lists, including "Do not repeat Hb A_{1c} testing in stable patients within 3 months of a previous result," "Do not order antinuclear antibodies and extractable nuclear antigens unless the patient is suspected to have a connective tissue disease," "Do not measure the INR (international normalized ratio) in patients who are taking an anti-Xa inhibitor," and "Do not employ a specific direct oral anticoagulant reversal agent without identifying the DOAC and estimating its plasma concentration" (85).

To facilitate wise test selection, electronic ordering systems can also be designed to either stop unnecessary testing or to gather important clinical information to help explain downstream test results. Some examples from hematology are (1) querying the need for routine coagulation tests, or other hemostasis tests, when an order for that test has already (or recently) been made (to avoid duplicate orders); (2) requesting information about patient anticoagulation (all possibilities); (3) requesting completion of a 4T score ahead of heparin-induced thrombocytopenia testing or a

PLASMIC (Platelet count; combined hemoLysis variable; absence of Active cancer; absence of Stem-cell or solid-organ transplant; MCV; INR; Creatinine) score ahead of ADAMTS13 (a disintegrin and metalloprotease with thrombospondin type 1 repeats, member 13) activity testing.

THE VIRTUOUS CIRCLE OF APPROPRIATENESS

The Implementation of an Environmental Management System and the Reduction of Inappropriate Testing Reduce Laboratory Costs

One positive consequence of EMS implementation is the reduction of costs (68). A dermatopathology laboratory saved US$43 000 per year through recycling procedures for plastic, alcohol and xylene reagents, formalin, and paper, as well as applying an electricity reduction plan (69). The Royal College of Pathologists of Australia Quality Assurance Programs have also integrated an EMS into their facilities. The focus was on reducing environmental impact through sustainable practices such as printing (cutting down on the number of printers, double-sided printing, user authentication, etc.), reducing electricity consumption (utilizing light-emitting diode lights and light sensors, implementing a switch-off policy, etc.), responsible waste management (using certified contractors for waste removal and regular waste container audits), recycling (supplies, batteries, paper, printer cartridges, etc.), and upholding a green purchasing policy. The improved environmental outcomes resulted in estimated savings of AUS$ 800 000 over a 3-year period (70). While the impact of individual tests or measures to mitigate them may seem insignificant, their accumulation can lead to significant large-scale results, particularly on a national scale (44). Furthermore, as laboratory tests incur costs, any unnecessary test results in avoidable expenses. For example, a military medical 425-bed inpatients center estimated that a program concentrating on eliminating superfluous thyroid function tests alone could result in cost savings of $120 000 per year (87).

There are multiple illustrations of interventions' impact in curbing improper laboratory testing leading to favorable financial outcomes. Tamburrano et al. (33) provided an assessment of the overuse of laboratory testing and associated costs in an Italian university hospital. They scrutinized 5 716 370 requests, of which 809 245 (14%) did not conform to predefined requesting rules. The avoidable expenditures were estimated to be €1 719 337 during a 20-month period (i.e., €85 967 per month). Vegting et al. (88) conducted a multifaceted intervention (education, guidelines, feedback) in the internal medicine department of an academic center to reduce inappropriate diagnostic testing for both in- and outpatients. The authors recorded a savings of €230 000 (21% of total costs) in 1 year. In a previous review focusing on interventions to improve the appropriateness of laboratory testing conducted in the ICU, 50% (n = 22) of interventions retrieved evaluated economic outcomes, all of which reported significant cost savings (89). The amount varied based on the specific tests, interventions, settings, and time periods. Collectively, these data show that reducing inappropriate laboratory test requests has a dual positive effect of decreasing both the environmental impact and unnecessary costs associated with these tests.

Reducing Inappropriate Laboratory Testing Mitigates Environmental Impacts

To the best of our knowledge (50), there are 2 interventional studies that have assessed the impact of a laboratory demand management strategy on environmental outcomes (Table 1). Both studies demonstrated a decrease in carbon footprint, accompanied by cost savings. McAlister et al. (52) conducted an interventional study designed to reduce the economic and environmental impact of inappropriate laboratory testing in the department of medicine of a 653-bed Australian hospital. This study evaluated an education-based, 6-month-long

intervention resulting in a 10% decrease in pathology test orders. Estimations indicated that achieving a 10% decrease in pathology test orders across the entire hospital could have resulted in savings of 1300 kg CO_2e and AUS$ 500 000. On a nationwide scale, the authors estimated that a 10% decrease in pathology testing could have led to a reduction of 135 000 kg CO_2e emissions, equivalent to driving 620 000 km (or 15.5 times the circumference of the earth) by car, and an annual cost reduction of AUS$ 56 million. Regan et al. (51) carried out a 32-month intervention, combining education-based (posters, stickers) and feedback-based (communication of results) strategies to reduce the overuse of unnecessary combined biochemistry tests in a 26-bed pediatric cardiology ward. The results showed a 13.5% reduction of clinical biochemistry tests throughout the course of intervention, leading to estimated savings of £11,300 and a reduction of 17 800 kg of CO_2e emissions.

Reducing Inappropriate Laboratory Testing Does Not Jeopardize Patient Safety

Efforts to mitigate inappropriate laboratory use and carbon footprint often encounter the challenge of ensuring patient safety. The *primum non nocere* (i.e., "first, do no harm") principle serves as the guiding framework for healthcare delivery, which entails that such initiatives and any resulting behavioral alterations must not jeopardize patient safety. Nevertheless, as previously stated, unsuitable testing practices can lead to adverse effects on patient safety (32) and should be minimized. Data show that the balance is in favor of reducing inappropriate tests. Generally, implementing interventions to reduce inappropriate tests does not lead to an increase in adverse clinical events. A review on interventions to improve laboratory testing in the ICU revealed that 60% of interventional studies monitored patient safety (with an average of 3 outcomes per study), and none of these reported any deterioration of safety outcomes in the postintervention period (89). A systematic review of interventions to reduce routine diagnostic tests (pathology and chest X-rays mixed) in the ICU analyzed 26 studies including a total of 40 000 patients and showed no significant disparities in safety outcomes, i.e., mortality, length of stay, or adverse events, between preintervention and postintervention periods, despite an overall low quality of studies (90). These data indicate feasible implementation of measures to decrease unnecessary laboratory testing while safeguarding patient safety.

CONCLUSIONS

At least one out of every 3 tests is impacted by inappropriateness, resulting in negative consequences on the 3Ps: People (hospital-acquired anemia and transfusion risks, risks of error, incidental findings and subsequent unnecessary interventions, patient discomfort and stress, staff overload), Profit (direct and indirect costs), and Planet (GHG emissions, water and air pollution, waste). These negative outcomes are part of a vicious circle.

Fortunately, many examples of interventions are published to improve the appropriate use of laboratory tests. Resources, tools, and support are increasingly available to aid the transition toward sustainable laboratories and healthcare. Implementing an environmental management system in (clinical) laboratories not only will contribute to more environment friendly practices but can also associate with significant net cost savings. These positive outcomes are mutually reinforcing in a virtuous circle.

Decreasing inappropriate laboratory testing decreases GHG emissions and reduces expenses while safeguarding patient safety. It is our responsibility, as citizens and healthcare professionals, to rethink our work habits and to drive and embrace change that will bring us toward a more sustainable healthcare system. There is a "win-win" opportunity for laboratory services all around the world to adopt appropriateness and environmentally friendly policies, leading them to become virtuous clinical diagnostic facilities.

Nonstandard Abbreviations: ICU, intensive care unit; GHG, greenhouse gas; CO_2e, carbon dioxide equivalent emissions; ISO, International Organization for Standardization; LCA, life cycle assessment; EMS, environmental management system.

Author Contributions: *The corresponding author takes full responsibility that all authors on this publication have met the following required criteria of eligibility for authorship: (a) significant contributions to the conception and design, acquisition of data, or analysis and interpretation of data; (b) drafting or revising the article for intellectual content; (c) final approval of the published article; and (d) agreement to be accountable for all aspects of the article thus ensuring that questions related to the accuracy or integrity of any part of the article are appropriately investigated and resolved. Nobody who qualifies for authorship has been omitted from the list.*

Luigi Devis (Conceptualization-Equal, Project administration-Equal, Visualization-Equal, Writing—original draft-Equal, Writing—review & editing-Equal), Mélanie Closset (Conceptualization-Equal, Project administration-Equal, Supervision-Equal, Validation-Equal, Writing—review & editing-Equal), Jonathan Degosserie (Project administration-Equal, Validation-Equal, Writing—review & editing-Equal), Sarah Lessire (Project administration-Equal, Validation-Equal, Writing—review & editing-Equal), Pauline Modrie (Project administration-Equal, Validation-Equal, Writing—review & editing-Equal), Damien Gruson (Project administration-Equal, Validation-Equal, Writing—review & editing-Equal), Emmanuel Favaloro (Project administration-Equal, Validation-Equal, Writing—review & editing-Equal), Giuseppe Lippi (Project administration-Equal, Validation-Equal, Writing—review & editing-Equal), Emilie Catry (Conceptualization-Equal, Project administration-Equal, Supervision-Equal, Validation-Equal, Writing—review & editing-Equal), and Francois Mullier (Conceptualization-Equal, Project administration-Equal, Supervision-Equal, Validation-Equal, Writing—review & editing-Equal)

Authors' Disclosures or Potential Conflicts of Interest: *Upon manuscript submission, all authors completed the author disclosure form*.

Research Funding: None declared.

Disclosures: F. Mullier has received speaker fees from Fresenius, Technoclone, Stago, and Werfen, all unrelated to this work. S. Lessire has received speaker fees at the BIRD congress in Bruges, Belgium in November 2023; travel support from the Network for the Advancement of Patient Blood Management, Haemostasis and Thrombosis (NATA) for the annual symposium in Athens, Greece, April 2023; travel support from NATA as a member of the medical board, Bologna, Italy, September 2023.

REFERENCES

1. Smellie WS. Demand management and test request rationalization. Ann Clin Biochem 2012;49(Pt 4):323–36.
2. Mrazek C, Haschke-Becher E, Felder TK, Keppel MH, Oberkofler H, Cadamuro J. Laboratory demand management strategies-an overview. Diagnostics (Basel) 2021;11:1141.
3. Hallworth MJ, Epner PL, Ebert C, Fantz CR, Faye SA, Higgins TN, et al. Current evidence and future perspectives on the effective practice of patient-centered laboratory medicine. Clin Chem 2015;61:589–99.
4. Lippi G. The irreplaceable value of laboratory diagnostics: four recent tests that have revolutionized clinical practice. EJIFCC 2019;30:7–13.
5. Lippi G, Plebani M. The add value of laboratory diagnostics: the many reasons why decision-makers should actually care. J Lab Precis Med 2017;2:100.
6. Lippi G, Bovo C, Ciaccio M. Inappropriateness in laboratory medicine: an elephant in the room? Ann Transl Med 2017;5:82.
7. Zhi M, Ding EL, Theisen-Toupal J, Whelan J, Arnaout R. The landscape of inappropriate laboratory testing: a 15-year meta-analysis. PLoS One 2013;8:e78962.
8. Cadamuro J, Gaksch M, Wiedemann H, Lippi G, von Meyer A, Pertersmann A, et al. Are laboratory tests always needed? Frequency and causes of laboratory overuse in a hospital setting. Clin Biochem 2018;54:85–91.
9. Shrank WH, Rogstad TL, Parekh N. Waste in the US health care system: estimated costs and potential for savings. JAMA 2019;322:1501–9.
10. Cappelletti P. Appropriateness of diagnostics tests. Int J Lab Hematol 2016;38:91–9.
11. Beastall GH. Adding value to laboratory medicine: a professional responsibility. Clin Chem Lab Med 2013;51:221–7.
12. Arshoff L, Hoag G, Ivany C, Kinniburgh D. Laboratory medicine: the exemplar for value-based healthcare. Healthc Manage Forum 2021;34:175–80.
13. Ferraro S, Braga F, Panteghini M. Laboratory medicine in the new healthcare environment. Clin Chem Lab Med 2016;54:523–33.
14. Koch CG, Li L, Sun Z, Hixson ED, Tang A, Phillips SC, et al. Hospital-acquired anemia: prevalence, outcomes, and healthcare implications. J Hosp Med 2013;8:506–12.
15. Witosz K, Wojnarowicz O, Krzych ŁJ. Iatrogenic blood loss due to daily laboratory testing and the risk of subsequent anaemia in intensive care unit patients: case series. Acta Biochim Pol 2021;68:135–8.

16. Holland J, Peralta RM, Moss RL, Feane K, Uprichard J. A single-centre review of iatrogenic anaemia in adult intensive care. Transfus Med 2020;30:196–200.
17. Lyon AW, Chin AC, Slotsve GA, Lyon ME. Simulation of repetitive diagnostic blood loss and onset of iatrogenic anemia in critical care patients with a mathematical model. Comput Biol Med 2013;43:84–90.
18. Abdallah R, Rai H, Panch SR. Transfusion reactions and adverse events. Clin Lab Med 2021;41:669–96.
19. Shamsasenjan K, Gharehdaghi S, Khalaf-Adeli E, Pourfathollah AA. New horizons for reduction of blood use: patient blood management. Asian J Transfus Sci 2023;17:108–16.
20. Sztefko K, Beba J, Mamica K, Tomasik P. Blood loss from laboratory diagnostic tests in children. Clin Chem Lab Med 2013;51:1623–6.
21. Carpenter CR, Raja AS, Brown MD. Overtesting and the downstream consequences of overtreatment: implications of "Preventing Overdiagnosis" for emergency medicine. Acad Emerg Med 2015;22:1484–92.
22. Gopalratnam K, Forde IC, O'Connor JV, Kaufman DA. Less is more in the ICU: resuscitation, oxygenation and routine tests. Semin Respir Crit Care Med 2016;37:23–33.
23. Grieme CV, Voss DR, Olson KE, Davis SR, Kulhavy J, Krasowski MD. Prevalence and clinical utility of "incidental" critical values resulting from critical care laboratory testing. Lab Med 2016;47:338–49.
24. Epner PL, Gans JE, Graber ML. When diagnostic testing leads to harm: a new outcomes-based approach for laboratory medicine. BMJ Qual Saf 2013;22(Suppl 2):ii6–10.
25. Lippi G, Plebani M. Laboratory "incidentalomas": facts or fiction? Eur J Intern Med 2010;21:572.
26. Bodley T, Levi O, Chan M, Friedrich JO, Hicks LK. Reducing unnecessary diagnostic phlebotomy in intensive care: a prospective quality improvement intervention. BMJ Qual Saf 2023:32:485–94.
27. Clark SL, Cunningham JL, Rabinstein AA, Wijdicks EFM. Electrolyte orders in the neuroscience intensive care unit: worth the value or waste? Neurocrit Care 2011;14:216–21.
28. Garay OU, Guiñazú G, Cornistein W, Farina J, Valentini R, Levy Hara G. Budget impact analysis of using procalcitonin to optimize antimicrobial treatment for patients with suspected sepsis in the intensive care unit and hospitalized lower respiratory tract infections in Argentina. PLoS ONE 2021;16:e0250711.
29. Gandhi TK, Kachalia A, Thomas EJ, Puopolo AL, Yoon C, Brennan TA, et al. Missed and delayed diagnoses in the ambulatory setting: a study of closed malpractice claims. Ann Intern Med 2006;145:488–96.
30. Cadamuro J, Simundic A-M, Von Meyer A, Haschke-Becher E, Keppel MH, Oberkofler H, et al. Diagnostic workup of microcytic anemia: an evaluation of underuse or misuse of laboratory testing in a hospital setting using the AlinIQ system. Arch Pathol Lab Med 2023;147:117–24.
31. Ferraro S, Panteghini M. The role of laboratory in ensuring appropriate test requests. Clin Biochem 2017;50:555–61.
32. Cadamuro J, Ibarz M, Cornes M, Nybo M, Haschke-Becher E, von Meyer A, et al. Managing inappropriate utilization of laboratory resources. Diagnosis (Berl) 2019;6:5–13.
33. Tamburrano A, Vallone D, Carrozza C, Urbani A, Sanguinetti M, Nicolotti N, et al. Evaluation and cost estimation of laboratory test overuse in 43 commonly ordered parameters through a Computerized Clinical Decision Support System (CCDSS) in a large university hospital. PLoS One 2020;15:e0237159.
34. van Walraven C, Raymond M. Population-based study of repeat laboratory testing. Clin Chem 2003;49:1997–2005.
35. Campbell-Lendrum D, Neville T, Schweizer C, Neira M. Climate change and health: three grand challenges. Nat Med 2023;29:1631–8.
36. Eckelman MJ, Sherman J. Environmental impacts of the U.S. Health Care System and Effects on Public Health. PLoS One 2016;11:e0157014.
37. Eckelman MJ, Sherman JD, MacNeill AJ. Life cycle environmental emissions and health damages from the Canadian healthcare system: an economic-environmental-epidemiological analysis. PLoS Med 2018;15:e1002623.
38. Malik A, Lenzen M, McAlister S, McGain F. The carbon footprint of Australian health care. Lancet Planet Health 2018;2:e27–35.
39. Nansai K, Fry J, Malik A, Takayanagi W, Kondo N. Carbon footprint of Japanese health care services from 2011 to 2015. Resour Conserv Recycl 2020;152:104525.
40. Wu R. The carbon footprint of the Chinese health-care system: an environmentally extended input–output and structural path analysis study. Lancet Planet Health 2019; 3:e413–9.
41. Pichler P-P, Jaccard IS, Weisz U, Weisz H. International comparison of health care carbon footprints. Environ Res Lett 2019;14:064004.
42. Farley M, Nicolet BP. Re-use of laboratory utensils reduces CO2 equivalent footprint and running costs. PLoS One 2023;18:e0283697.
43. Malik A, Padget M, Carter S, Wakiyama T, Maitland-Scott I, Vyas A, et al. Environmental impacts of Australia's largest health system. Resour Conserv Recycl 2021;169:105556.
44. McAlister S, Barratt AL, Bell KJ, McGain F. The carbon footprint of pathology testing. Med J Aust 2020;212:377–82.
45. Spoyalo K, Lalande A, Rizan C, Park S, Simons J, Dawe P, et al. Patient, hospital and environmental costs of unnecessary bloodwork: capturing the triple bottom line of inappropriate care in general surgery patients. BMJ Open Quality 2023;12:e002316.
46. Breth-Petersen M, Bell K, Pickles K, McGain F, McAlister S, Barratt A. Health, financial and environmental impacts of unnecessary vitamin D testing: a triple bottom line assessment adapted for healthcare. BMJ Open 2022;12: e056997.
47. Savoldelli A, Landi D, Rizzi C. Sustainability in healthcare: methods and tools for the assessment. Stud Health Technol Inform 2023;301:186–91.
48. McAlister S, Morton RL, Barratt A. Incorporating carbon into health care: adding carbon emissions to health technology assessments. Lancet Planet Health 2022;6:e993–9.
49. Varughese S, Ahmed R. Environmental and occupational considerations of anesthesia: a narrative review and update. Anesth Analg 2021;133:826–35.

50. Batcup C, Breth-Petersen M, Dakin T, Barratt A, McGain F, Newell BR, et al. Behavioural change interventions encouraging clinicians to reduce carbon emissions in clinical activity: a systematic review. BMC Health Serv Res 2023;23: 384.
51. Regan W, Hothi D, Jones K. Sustainable approach to reducing unnecessary combined biochemistry tests on a paediatric cardiology ward. BMJ Open Qual 2018;7: e000372.
52. McAlister S, Smyth B, Koprivic I, Di Tanna G L, McGain F, Charlesworth K, et al. Carbon emissions and hospital pathology stewardship: a retrospective cohort analysis. Intern Med J 2023;53:584–9.
53. Keogh S, Mathew S, Ullman AJ, Rickard CM, Coyer F. What blood conservation practices are effective at reducing blood sampling volumes and other clinical sequelae in intensive care? A systematic review. Aust Crit Care 2023; 36:1129–37.
54. Siegal DM, Belley-Côté EP, Lee SF, Hill S, D'Aragon F, Zarychanski R, et al. Small-volume blood collection tubes to reduce transfusions in intensive care: the STRATUS randomized clinical trial. JAMA 2023;330:1872–81.
55. Wu Y, Spaulding AC, Borkar S, Shoaei MM, Mendoza M, Grant RL, et al. Reducing blood loss by changing to small volume tubes for laboratory testing. Mayo Clin Proc Innov Qual Outcomes 2021;5:72–83.
56. International Organization for Standardization (ISO). ISO14001 and related standards: Environmental management 2023. https://www.iso.org/iso-14001-environmental-management.html (Accessed July 2024).
57. Guirado-Fuentes C, Abt-Sacks A, Trujillo-Martín MDM, García-Pérez L, Rodríguez-Rodríguez L, Carrion I, et al. Main challenges of incorporating environmental impacts in the economic evaluation of health technology assessment: a scoping review. Int J Environ Res Public Health 2023;20:4949.
58. Amukele TK, Hernandez J, Snozek CLH, Wyatt RG, Douglas M, Amini R, et al. Drone transport of chemistry and hematology samples over long distances. Am J Clin Pathol 2017;148:427–35.
59. Lippi G, Mattiuzzi C. Biological samples transportation by drones: ready for prime time? Ann Transl Med 2016;4:92.
60. Madhusoodanan J. What can you do to make your lab greener? Nature 2020;581:228–9.
61. European Federation of Clinical Chemistry and Laboratory Medicine (EFLM) Task Force: Green and Sustainable Laboratories (TF-GSL). EFLM guidelines for green and sustainable medical laboratories. Milan (Italy): EFLM; 2022.
62. Yusuf E, Luijendijk A, Roo-Brand G, Friedrich AW. The unintended contribution of clinical microbiology laboratories to climate change and mitigation strategies: a combination of descriptive study, short survey, literature review and opinion. Clin Microbiol Infect 2022; 28:1245–50.
63. Fan BE, Tan JG, Favaloro EJ. Reducing our carbon footprint in the haematology laboratory: a shared responsibility. Int J Lab Hematol 2023;45:778–80. Preprint at doi:10.1055/s-0044-1787661.
64. Thonon H, Van Nieuwenhove M, Thachil J, Lippi G, Hardy M, Mullier F. Hemostasis testing in the emergency department: a narrative review. Semin Thromb Hemost 2024.
65. Fragão-Marques M, Ozben T. Digital transformation and sustainability in healthcare and clinical laboratories. Clin Chem Lab Med 2023;61:627–33.
66. Gruson D, Helleputte T, Rousseau P, Gruson D. Data science, artificial intelligence, and machine learning: opportunities for laboratory medicine and the value of positive regulation. Clin Biochem 2019;69:1–7.
67. Molero A, Calabrò M, Vignes M, Gouget B, Gruson D. Sustainability in healthcare: perspectives and reflections regarding laboratory medicine. Ann Lab Med 2021;41: 139–44.
68. Badrick T. The role of laboratories in reducing the carbon footprint. Am J Clin Pathol 2022;158:322–4.
69. Chisholm C, Hayford K, Stewart M. Dermatopathology laboratory green initiatives. Am J Clin Pathol 2022;158: 372–7.
70. Ross J, Penesis J, Badrick T. Improving laboratory economic and environmental performance by the implementation of an environmental management system. Accredit Qual Assur 2019;24:319–27.
71. Lopez JB, Badrick T. Proposals for the mitigation of the environmental impact of clinical laboratories. Clin Chem Lab Med 2012;50:1559–64.
72. Lopez JB, Jackson D, Gammie A, Badrick T. Reducing the environmental impact of clinical laboratories. Clin Biochem Rev 2017;38:3–11.
73. Ozben T, Fragão-Marques M. Chemical strategies for sustainable medical laboratories. Clin Chem Lab Med 2023;61:642–50.
74. Scott S. Embedding education into clinical laboratory professional training to foster sustainable development and greener practice. Clin Chem Lab Med 2023;61: 638–41.
75. Yu J-R, Chen C-H, Huang T-W, Lu J-J, Chung C-R, Lin T-W, et al. Energy efficiency of inference algorithms for clinical laboratory data sets: green artificial intelligence study. J Med Internet Res 2022;24:e28036.
76. Müller H, Holzinger A, Plass M, Brcic L, Stumptner C, Zatloukal K. Explainability and causability for artificial intelligence-supported medical image analysis in the context of the European In Vitro Diagnostic Regulation. N Biotechnol 2022;70:67–72.
77. Li B, Qi P, Liu B, Di S, Liu J, Pei J, et al. Trustworthy AI: from principles to practices. Preprint at https://doi.org/10.48550/arXiv.2110.01167 (2022).
78. Aziz HA, Alshekhabobakr HM. Health informatics tools to improve utilization of laboratory tests. Lab Med 2017;48: e30–5.
79. MacMillan TE, Gudgeon P, Yip PM, Cavalcanti RB. Reduction in unnecessary red blood cell folate testing by restricting computerized physician order entry in the electronic health record. Am J Med 2018;131:939–44.
80. Sustainable Healthcare Coalition. Who we are. 2023. https://shcoalition.org/who-we-are/ (Accessed July 2024).

81. University College London (UCL). Laboratory Efficiency Assessment Framework. 2023. https://www.ucl.ac.uk/sustainable/leaf-laboratory-efficiency-assessment-framework (Accessed July 2024).

82. My Green Lab (mygreenlab.org). Programs. https://www.mygreenlab.org/programs.html (Accessed July 2024).

83. Internation Federation of Clinical Chemistry and Laboratory Medicine (IFCC). Task Force Environmental Impact of Laboratory Medicine (TF-EILM) 2023. https://ifcc.org/executive-board-and-council/eb-task-forces/task-force-environmental-impact-of-laboratory-medicine-tf-eilm/ (Accessed July 2024).

84. European Federation of Clinical Chemistry and Laboratory Medicine (EFLM). Task Force: Green and Sustainable Laboratories (TF-GSL) 2023. https://www.eflm.eu/site/page/a/1730 (Accessed July 2024).

85. American Society for Clinical Pathology (ASCP). About Choosing Wisely 2023. https://www.ascp.org/content/get-involved/choosing-wisely# (Accessed July 2024).

86. ABIM Foundation. Choosing Wisely 2023. https://www.choosingwisely.org/ (Accessed July 2024).

87. Kluesner JK, Beckman DJ, Tate JM, Beauvais AA, Kravchenko MI, Wardian JL, et al. Analysis of current thyroid function test ordering practices. J Eval Clin Pract 2018;24:347–52.

88. Vegting IL, van Beneden M, Kramer MH, Thijs A, Kostense PJ, Nanayakkara PW. How to save costs by reducing unnecessary testing: lean thinking in clinical practice. Eur J Intern Med 2012;23:70–5.

89. Devis L, Catry E, Honore PM, Mansour A, Lippi G, Mullier F, et al. Interventions to improve appropriateness of laboratory testing in the intensive care unit: a narrative review. Ann Intensive Care 2024;14:9.

90. Hooper KP, Anstey MH, Litton E. Safety and efficacy of routine diagnostic test reduction interventions in patients admitted to the intensive care unit: a systematic review and meta-analysis. Anaesth Intensive Care 2021;49:23–34.