

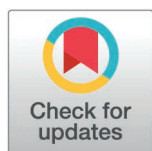
RESEARCH ARTICLE

# Environmental impacts of laboratory and scientific equipment: Focus on equipment operation and procurement

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## Abstract

Climate change and environmental sustainability are major priorities across scientific and policy domains. Scientists themselves are starting to recognize that their own activities have direct and indirect environmental impacts. These impacts result from things like material and energy use and waste generation in conducting scientific research, particularly in laboratories. In this article, we build upon growing efforts to measure and manage these environmental impacts by conducting cradle-to-grave life cycle assessments (LCAs) of widely used scientific and laboratory equipment. We considered over 3000 pieces of equipment used by Government of Canada laboratories. Our study contributes in four ways. First, although previous work has examined laboratory consumables and other impact drivers like building energy consumption and transportation, our study draws attention to the environmental impacts of laboratory and scientific equipment. Second, our study demonstrates a novel approach for screening large and varied sets of equipment to prioritize equipment with the highest potential environmental impacts. Third, our study broadens the scope of assessment with respect to system boundaries (i.e., cradle-to-grave) and environmental impacts (i.e., beyond GHG emissions). Finally, our study connects equipment-level LCA results to sustainability transformations by highlighting leverage points informed by the life cycle profile of equipment. Our results suggest a tendency for laboratory and scientific equipment to be use-intensive (as seen, e.g., in the case of refrigerators and freezers where the use stage accounts for approximately 97% of life cycle GHG emissions). However, this life cycle profile varies across environmental indicators (e.g., climate change, acidification, smog formation, and ecological toxicity) and with changes in equipment usage frequency (i.e., hours per year in operation). Some equipment, like scanning electron microscopes, can be production-intensive. These findings suggest that sustainability transformations for laboratory equipment need to consider the life cycle profile of the equipment and involve leverage points beyond procurement decisions.

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## Author summary

Scientists are starting to recognize that their own activities, particularly in the procurement and operation of equipment used in research laboratories, contribute to climate change and other environmental impacts. In this study, we considered more than 3000 pieces of scientific and laboratory equipment used in Government of Canada laboratories. We developed a new approach to screening equipment with the highest potential environmental impacts. Our analysis of high-impact equipment suggests that laboratory and scientific equipment tend to be use-intensive, meaning that the biggest impacts are from the operation of the equipment – primarily in electricity use for equipment like laboratory refrigerators, pumps, and compressors. However, this can change depending on how intensively the equipment is used (i.e., hours/day and days/week) and what types of environmental impacts (climate change, toxicity, etc.) are considered. These results suggest that actions to reduce environmental impacts need to be informed by an evaluation of the largest sources of these impacts. Impact reduction measures must extend beyond equipment procurement decisions.

## 1. Introduction

Climate change and environmental sustainability are major priorities across scientific and policy domains. Scientists themselves are starting to recognize that their own activities have direct and indirect environmental impacts [1–5]. For example, laboratory facilities can be five to ten times more energy intensive per unit of floor area than office buildings [6].

In this article, we investigate the environmental impacts of widely used scientific and laboratory equipment using the internationally standardized approach [7,8] of life cycle assessment (LCA). The life cycle of a product, like a piece of laboratory equipment, includes the extraction of raw materials, the manufacturing and assembly of the equipment, the shipping of the equipment to the laboratory, the use of the equipment in the laboratory, and the disposal of the equipment at the end of its lifespan (i.e., from cradle to grave).

Previous applications of LCA related to scientific research and laboratories include a study of greenhouse gas (GHG) emissions from the production of chemical solvents [9], along with a review of carbon footprints of the production and disposal of single-use consumables like well plates, pipette tips, and nitrile gloves [1]. Notably, although the term “carbon footprint” is often used synonymously with LCA, a true LCA, as defined by international standards, considers multiple environmental impacts [7,8]. Along with climate change, commonly evaluated environmental impacts include acidification, eutrophication, and human and ecological toxicity. The comprehensiveness of LCA with respect to life cycle stages and environmental impacts is important for avoiding problem-shifting that could result from a narrower focus on a single life cycle stage (e.g., production or end-of-life only) or environmental issue (e.g., GHG emissions only) [10].

The French GES 1point5 database uses LCA and environmentally extended economic input-output analysis (EEIO) to estimate emissions from laboratories, including upstream emissions attributable to purchases [2,3,11]. Unlike LCA, which is based on physical flows of materials and energy, EEIO is based on monetary exchanges of goods and services between economic sectors. Compared to LCA this approach is more aggregated and is generally better suited to large-scale national or sectoral analyses such as those that have been done in the healthcare sector [12–16]. Along with the “macro” (EEIO) and “micro” (LCA) approaches, the French database also uses a “meso” approach that is based on a representative (supplier) company selling a given type of product [2].

Our study uses LCA to evaluate the environmental impacts of laboratory and scientific equipment operated by Government of Canada laboratories. This equipment, selected based on environmental and economic criteria, includes:

- pumps,
- compressors,
- refrigerators and freezers,
- carbon dioxide incubators, and
- scanning electron microscopes.

Although our study concerns equipment used in Government of Canada laboratories, similar equipment is used in laboratories generally.

Our study contributes in four ways. First, although previous work has examined laboratory consumables and other impact drivers like building energy consumption and transportation, our study draws attention to the environmental impacts of laboratory and scientific equipment. Second, our study demonstrates a novel approach for screening large and varied sets of equipment to prioritize LCAs of equipment with the highest environmental impacts. Third, our study broadens the scope of assessment with respect to system boundaries (i.e., cradle-to-grave) and environmental impacts (i.e., beyond GHG emissions). Finally, our study connects equipment-level LCA results to sustainability transformations by highlighting leverage points [17] informed by the life cycle profile of equipment (i.e., the proportion of total life cycle environmental impacts from each life cycle stage).

Our LCA results suggest a tendency for laboratory and scientific equipment to be use-intensive, meaning that the life cycle environmental impacts are dominated by the operation of the equipment (e.g., electricity to run laboratory refrigerators and freezers). However, this life cycle profile varies across environmental indicators (e.g., climate change, acidification, smog formation, and ecological toxicity) and with changes in equipment usage frequency (i.e., hours per year in operation). Moreover, some equipment, like scanning electron microscopes, can be production-intensive, meaning that the upstream production of the equipment and its constituent materials is the dominant contributor to life cycle environmental impacts. These findings point towards different leverage points for sustainability transformations that extend beyond equipment procurement decisions.

## 2. Results

As can be seen in Fig 1, the life cycle profile of pumps varies considerably between environmental indicators. Although in the baseline scenario the use stage contributes significantly across all indicators, the production stage is also significant for acidification and smog formation. For indicators most directly related to human and ecological health (carcinogenic effects, non-carcinogenic effects, particulate matter formation, and ecotoxicity), the production stage is either dominant or of similar magnitude to the use stage. The contribution of distribution and end-of-life is comparatively small across all indicators. In the low usage frequency scenario (52 hours/year), pumps are highly production-intensive across all indicators. The life cycle profile of compressors is similar to that of pumps (Fig 2).

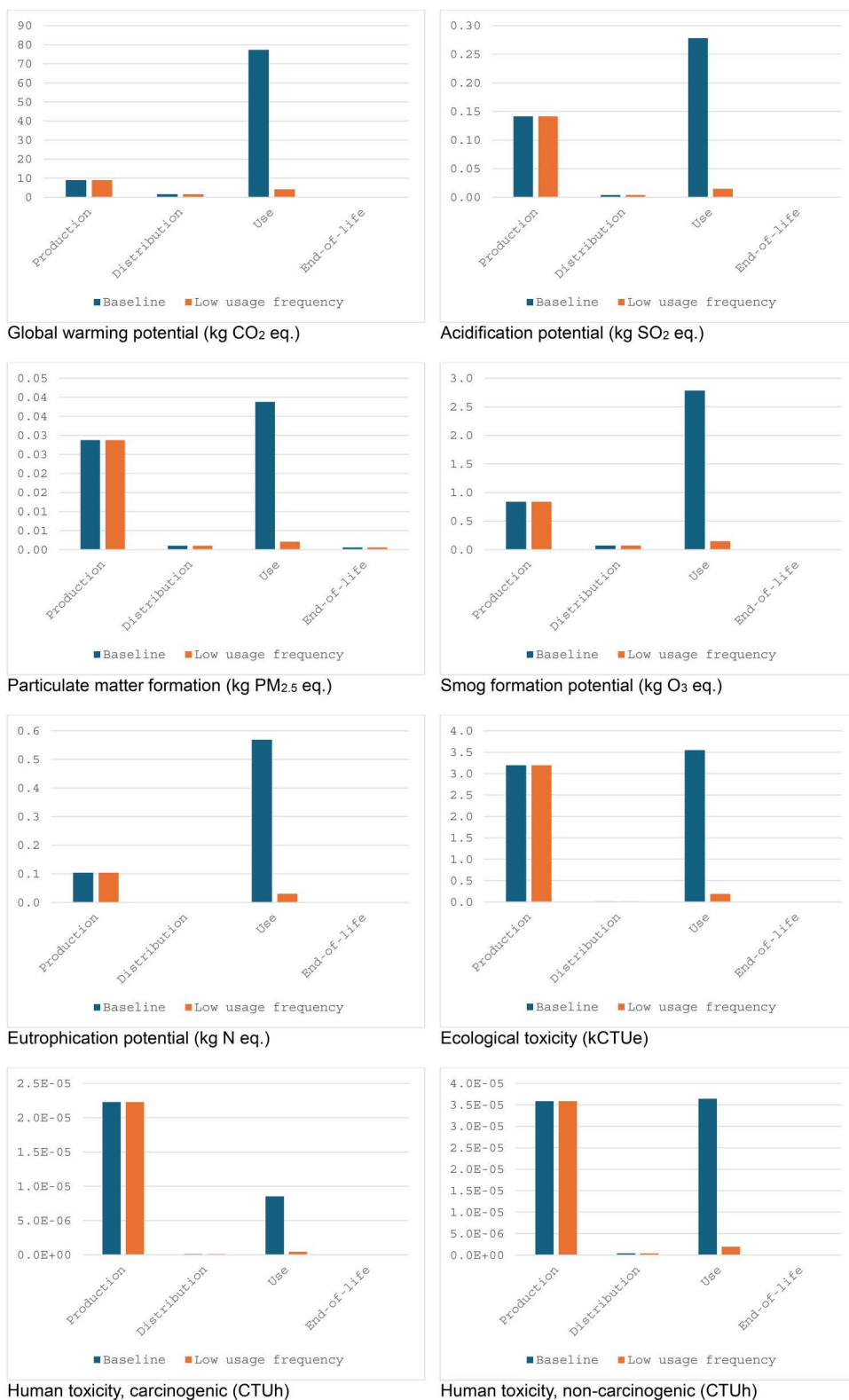


**Fig 1. Contribution analysis for pumps (low usage frequency = 52 hours/year, baseline = 966 hours/year).** The functional unit is defined as a 40W pump with a life expectancy of 10 years.

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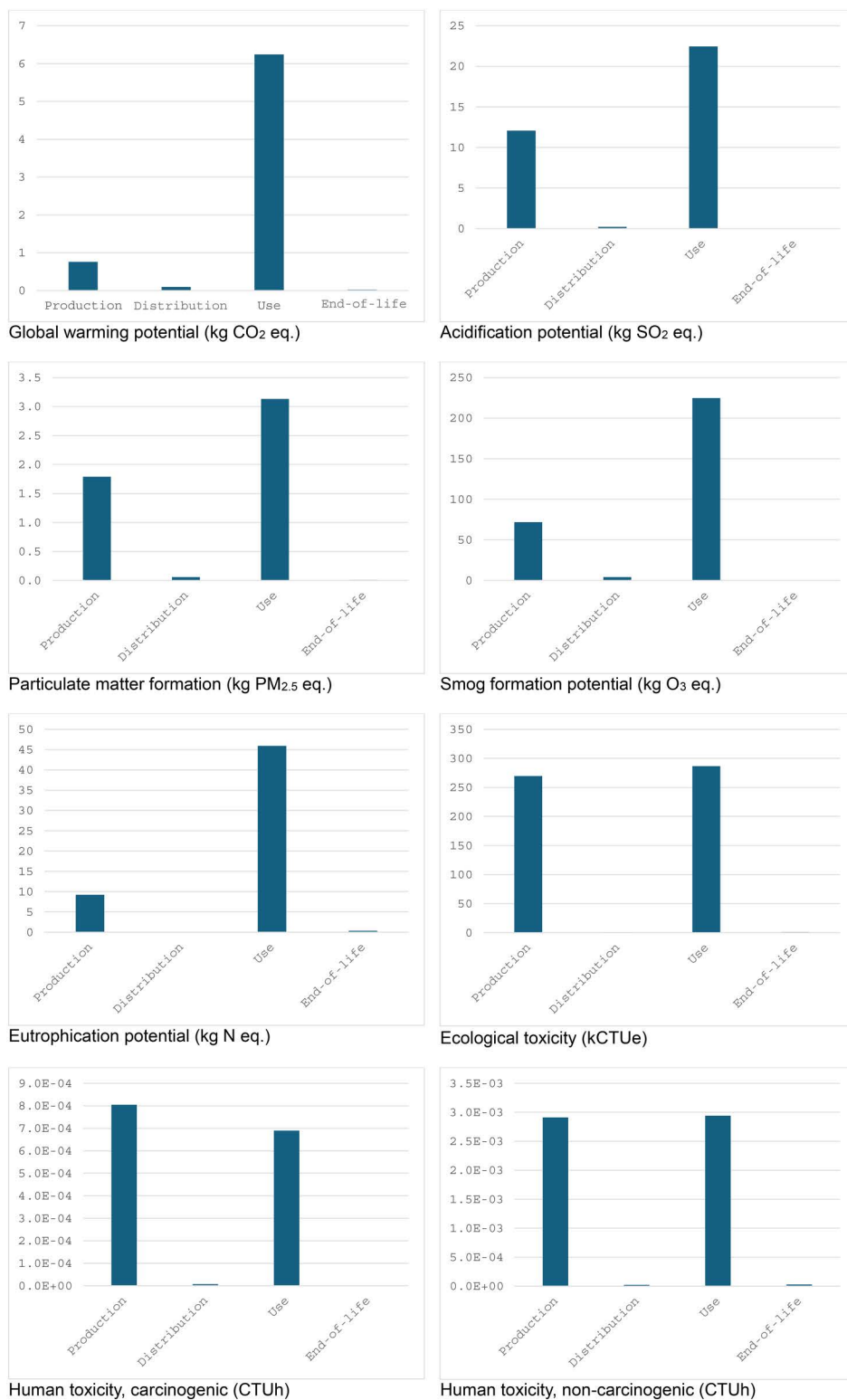


**Fig 2. Contribution analysis for compressors (usage frequency = 624 hours/year).** The functional unit is defined as a 4kW compressor with a life expectancy of 15 years.

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Refrigerators and freezers are use-intensive across all indicators (Fig 3).

As can be seen in Fig 4, the life cycle profile of carbon dioxide incubators is similar to that of refrigerators and freezers (noting that the ecoinvent refrigerator production process was also used to approximate the production of carbon dioxide incubators), with the addition of CO<sub>2</sub> gas as a consumable in the use stage, wherein we assume that all of the CO<sub>2</sub> gas used in the incubator is released to the environment. The low usage frequency scenario (130 hours/year) dramatically reduces the environmental impacts of carbon dioxide incubators, and the life cycle profile becomes notably production-intensive with respect to acidification, smog and particulate matter formation, and human toxicity (carcinogenic and non-carcinogenic). End-of-life, particularly treatment of scrap copper, becomes dominant with respect to ecological toxicity.

In contrast to the other equipment assessed, scanning electron microscopes are production-intensive across all environmental indicators (Fig 5). Notably, the end-of-life stage is significant with respect to ecotoxicity. As with carbon dioxide incubators, the end-of-life ecotoxicity impacts of scanning electron microscopes are largely driven by treatment of scrap copper in the disposal of the equipment.

### 3. Discussion

Aside from providing new LCA data and results for scientific and laboratory equipment, with a broader scope of assessment (i.e., with respect to life cycle stages and environmental issues) than in previous work, we have demonstrated a novel approach for screening large and varied sets of equipment to prioritize LCAs of equipment with the highest environmental impacts. As elaborated in section 4.2, the novelty of our approach is in grouping equipment using a standardized classification system, the United Nations Standard Products and Services Codes (UNSPSC), with LCA proxy products for each equipment group, to provide a first estimate of the production and end-of-life impacts of each piece of equipment. This bottom-up approach contrasts with top-down approaches, based on EEIO analysis, that are widely used in estimating the environmental impacts of large sets of products – as in the French GES 1point5 database cited previously [2,3,11].

A major shortcoming of EEIO analysis for assessing product-level environmental impacts is its high level of aggregation; for example, the closest match to laboratory and scientific equipment in Exiobase – a widely used EEIO database – might be “machinery and equipment not elsewhere classified” or “medical, precision and optical instruments, watches and clocks” [18]. Providing aggregated emissions estimates for such broad categories, which may not be good proxies for laboratory and scientific equipment, does little to inform measures to reduce environmental impacts attributable to the equipment. Moreover, because EEIO emissions estimates are expressed per unit of expenditure, the implication is that emissions can only be reduced by reducing expenditure – either by purchasing less equipment or by purchasing cheaper equipment which might have *higher* emissions. Further, EEIO omits the use and end-of-life stages of the product life cycle [19–23], which are particularly relevant to scientific and laboratory equipment that uses energy and consumables in its operation; omission of life cycle stages can result in problem-shifting rather than reduction in total life cycle environmental impacts. In other words, EEIO has limited value for informing sustainability transformations.

Our LCA results suggest a tendency for laboratory and scientific equipment to be use-intensive, i.e., with life cycle environmental impacts dominated by the use stage. Notably, all the equipment assessed in our study uses electricity in its operation, and most of the equipment (particularly pumps, compressors, refrigerators, and freezers) comprises versions of general equipment and appliances used across many industries. The finding of these appliances and equipment being use-intensive is consistent with previous LCA experience [24,25].

It is also notable that the usage frequency (i.e., hours per day and days per week in operation) can have a dramatic effect on the LCA results, potentially making the difference between a use-intensive product and a production-intensive product (as observed for pumps and carbon dioxide incubators). As in this study the use stage is comprised entirely of electricity consumption (with the addition of CO<sub>2</sub> gas used in the carbon dioxide incubator), the source of electricity can have a similar effect; lowering (raising) the impacts of electricity supply would lower (raise) the contribution of the use stage relative to the production stage. Another key factor is the power consumption of the equipment; a lower (higher)

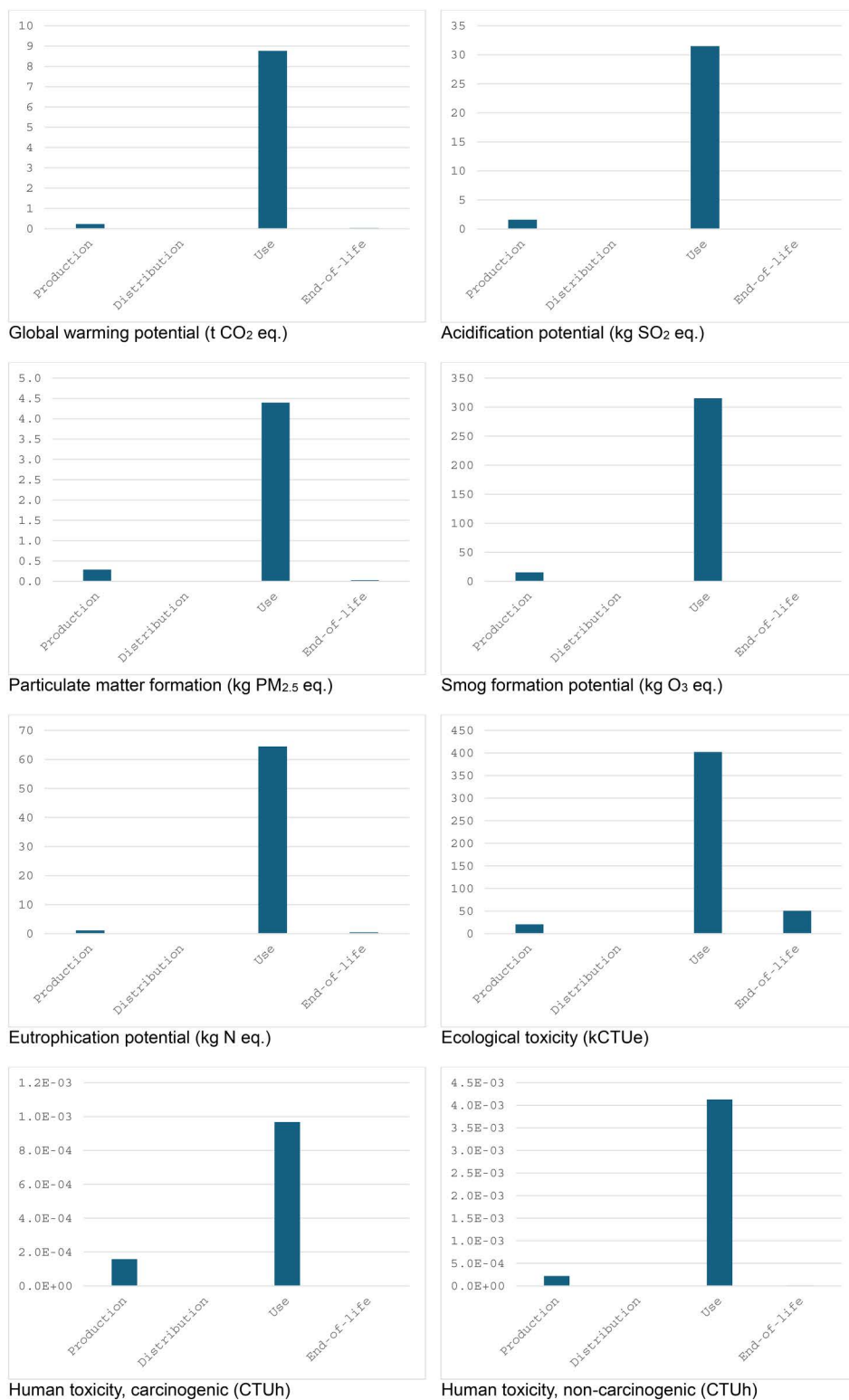


**Fig 3. Contribution analysis for refrigerators and freezers (continuous usage).** The functional unit is defined as a refrigerator or freezer, modelled as a typical domestic refrigerator, with a life expectancy of 10 years.

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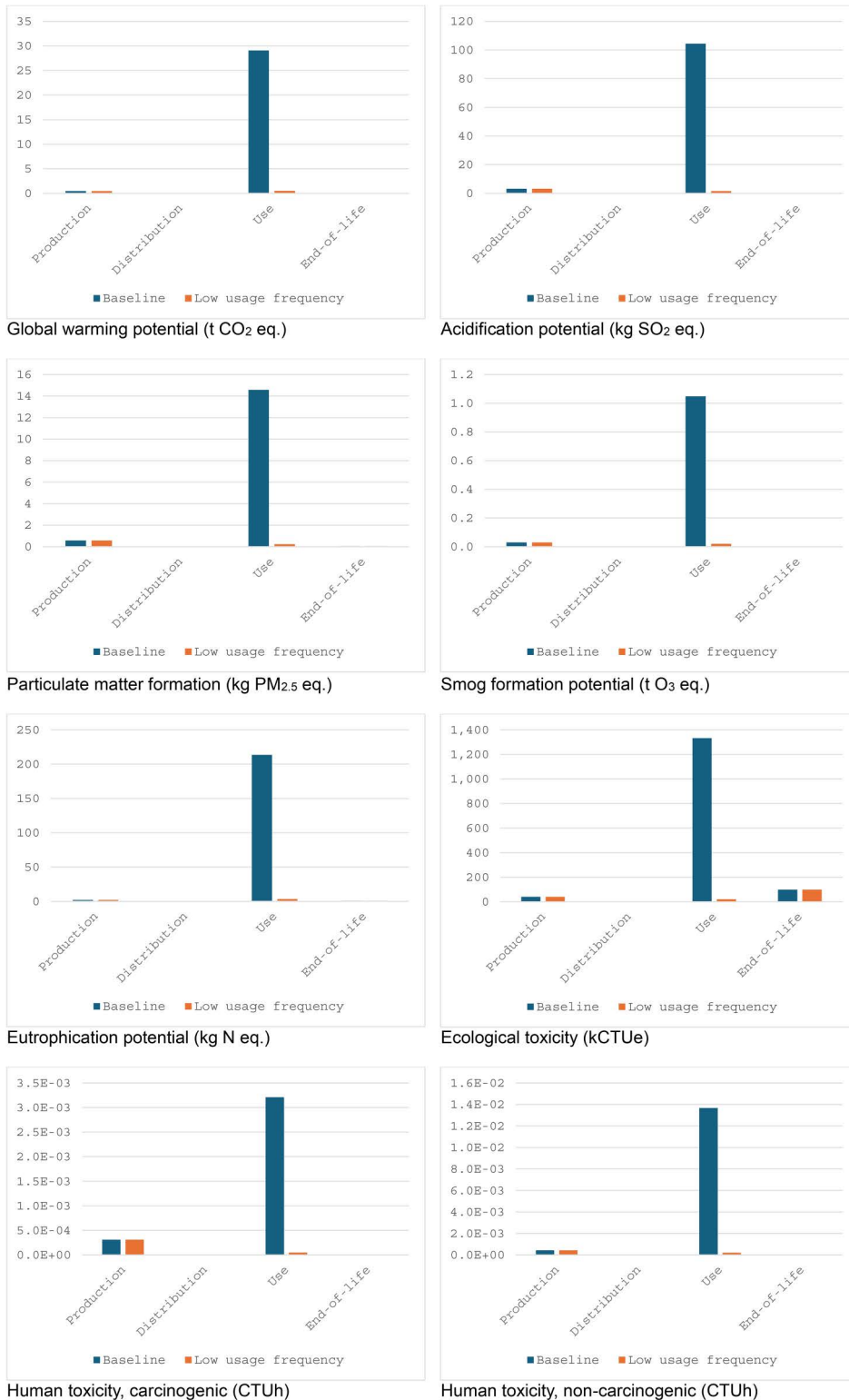


**Fig 4. Contribution analysis for carbon dioxide incubators (low usage frequency = 130 hours/year, baseline = continuous usage).** The functional unit is defined as a carbon dioxide incubator with approximately 184 L capacity and a life expectancy of 15 years.

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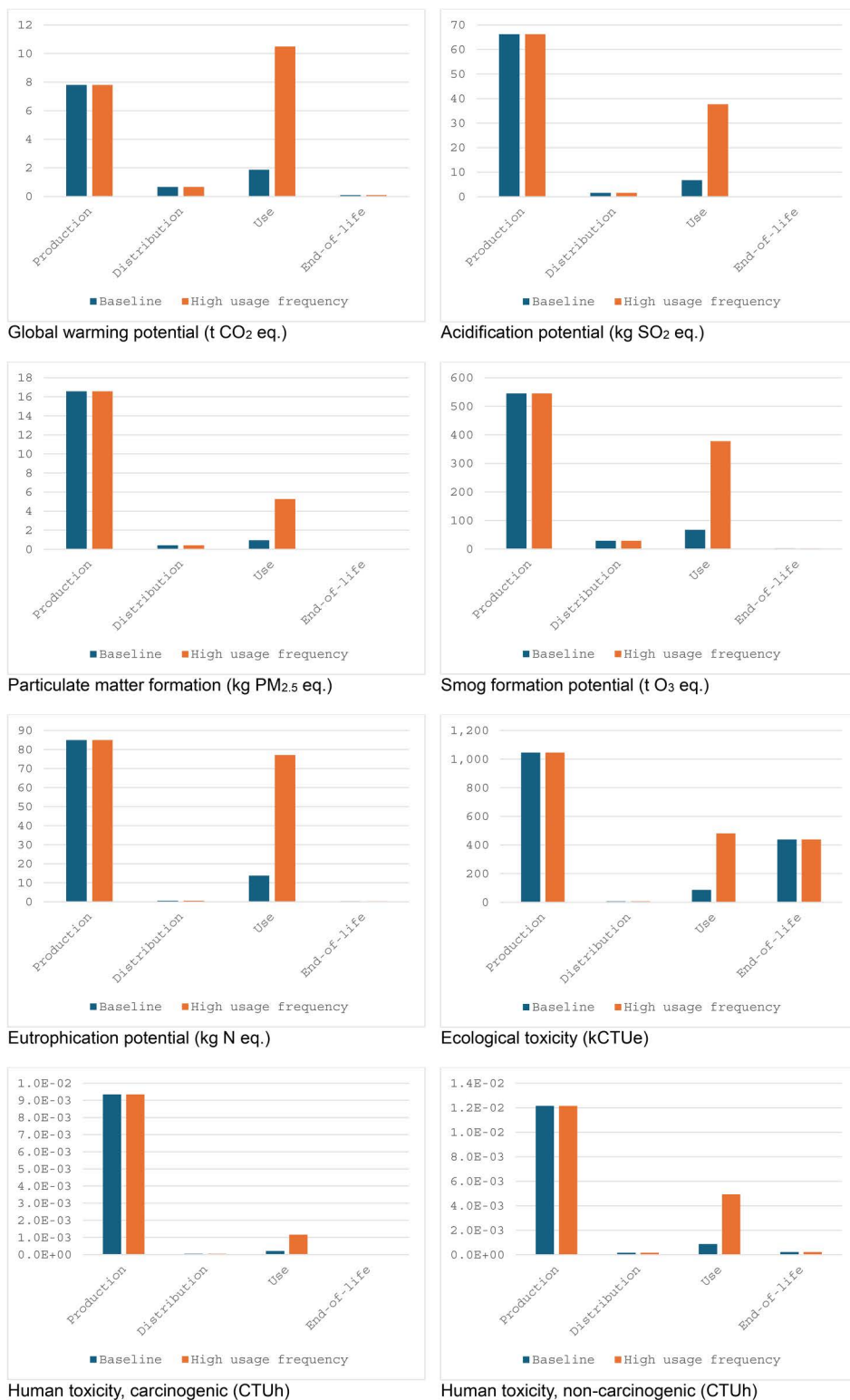


**Fig 5. Contribution analysis for scanning electron microscopes (high usage frequency = 2,912 hours/year, baseline = 520 hours/year).** The functional unit is defined as a scanning electron microscope with a mass of approximately 1000 kg and a life expectancy of 15 years.

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power value would lower (raise) the contribution of the use stage relative to the production stage. All these factors (usage frequency, power consumption, and electricity supply) have a direct linear relationship to use-stage impacts; if any one of these factors is doubled, the use-stage impacts are also doubled.

In contrast to the other equipment categories, scanning electron microscopes are production-intensive, even when assuming a usage frequency of nearly 3000 hours per year. While acknowledging that scanning electron microscopes have the most limited data of all the equipment assessed, this finding bears some similarity to our previous LCA study of dental X-ray equipment [26]. In that study, in which we constructed a detailed bill of materials based on manufacturer specifications, we found that the production of the X-ray machine dominated the life cycle environmental impacts, in part because the operation of the machine (i.e., for dental X-ray scans) used only a small amount of electricity. Analogously, data from Laboratories Canada indicates that the scanning electron microscope considered in our present study consumes no more than 1200 W of electrical power – comparable to a typical household microwave oven. Unlike a microwave oven, however, the scanning electron microscope weighs 1000 kg. Moreover, a scanning electron microscope, not unlike an X-ray machine, is highly specialized in its design and material composition – a characteristic previously found to be associated with disproportionately large environmental impacts relative to the size and weight of a product [27].

The life cycle profile can vary between different environmental indicators, however. For some equipment, particularly pumps and compressors, the use stage dominates with respect to global warming potential, whereas the production stage makes a sizeable, and sometimes dominant, contribution with respect to other indicators like acidification and human carcinogenicity. This finding suggests that a “carbon footprint” study of laboratory equipment, in which GHG emissions is the only environmental indicator considered, could overlook other important environmental issues.

Nonetheless, varied life cycle profiles between indicators do not necessarily lead to problem-shifting, as the impacts of the production and use stages of the equipment life cycle can be reduced independently. Using cleaner electricity in the operation of the equipment, or using the equipment more efficiently (e.g., by optimizing freezer temperature settings), does not affect the production of the equipment. Moreover, closer examination of our LCA results (see [S2 File](#) through [S6 File](#)) shows that the impacts of the production stage tend to be dominated by the production of metallic components made of steel, iron, copper, and aluminum. The upstream extractive processes in the supply-chains of these materials have impacts that can vary by orders of magnitude depending on the geographic location and technology used [28,29]. Sourcing lower-impact materials does not affect the use stage of the equipment. Problem-shifting between environmental indicators could be of greater concern when making comparisons of equipment, such as in making a purchasing decision considering different equipment with similar functions (e.g., pumps with different material composition or energy efficiency).

It is also notable that the distribution and end-of-life stages make a comparatively minor contribution to life cycle impacts irrespective of the indicator in question (except ecotoxicity for scanning electron microscopes); in other words, there are few, if any, distribution-intensive or disposal-intensive products. This finding is consistent with those from LCA studies in many other industries, including food and agriculture – wherein “buying local” contributes little to reducing total GHG emissions [30]. “Buying local” is a popular example of a “highly tangible, but essentially weak” [17] leverage point for sustainability transformations.

Our findings – regarding use-intensive vs. production-intensive equipment – point towards different leverage points for sustainability transformations. For use-intensive equipment, interventions targeting equipment operation have the greatest potential reductions in life cycle environmental impacts. Relatively shallow leverage points like adjusting the temperature set points of refrigerators and freezers [31] or avoiding continuous operation of vacuum pumps [32] could therefore be highly effective. For production-intensive equipment, deeper leverage points are needed, as the largest sources of environmental impacts are buried deep within equipment supply-chains upstream of the laboratories that purchase and operate the equipment.

Hence, our LCA results provide three lessons for sustainability transformations of scientific and laboratory equipment. First, transformational interventions need to target leverage points that are informed by the life cycle profile of the equipment. Second, while the literature on sustainability transformations tends to view shallower interventions – like changing freezer temperature settings – as less effective than deeper interventions [17], our LCA results suggest that such shallow interventions can be highly effective in reducing environmental impacts if the leverage points target “hotspots” in the life cycle profile. Finally, sustainability interventions need to extend beyond equipment procurement decisions and consider other leverage points such as equipment pooling [2].

## 4. Conclusion

In this article, we have conducted cradle-to-grave LCAs of widely used scientific and laboratory equipment, considering over 3000 pieces of equipment used by Government of Canada laboratories. Our results suggest a tendency for this equipment to be use-intensive (i.e., with the largest share of life cycle environmental impacts attributable to the operation of the equipment). However, the life cycle profile varies across environmental indicators (e.g., climate change, acidification, smog formation, and ecological toxicity) and with changes in equipment usage frequency (i.e., hours per year in operation). Some equipment, like scanning electron microscopes, can be production-intensive, meaning that the life cycle profile is dominated by the upstream production of the equipment. Viewed through the lens of sustainability transformations, our LCA results suggest that sustainability interventions need to consider the life cycle profile of the equipment and involve leverage points beyond procurement decisions.

## 5. Methods

According to international standards [7,8], LCA comprises four methodological steps:

1. goal and scope definition,
2. life cycle inventory analysis,
3. life cycle impact assessment, and
4. life cycle interpretation.

### 5.1. Goal and scope definition

As part of the Government of Canada’s Greening Government Strategy, the goal of this LCA study is to inform measures to reduce environmental impacts in the procurement and operation of laboratory and scientific equipment managed by Laboratories Canada. The study will inform these measures by providing estimates of environmental impacts of equipment over its whole life cycle, including production, use, and end-of-life. This information will help Laboratories Canada prioritize measures to reduce the largest sources of environmental impacts (i.e., “hotspots”) based on which equipment, and which stages of the equipment life cycle, contribute the most to the total impacts. The results are not intended to be used in comparative assertions (e.g., refrigerator A is environmentally preferable to refrigerator B) intended to be disclosed to the public. A total of 5006 pieces of equipment were initially considered for analysis; this number was reduced to 3470 pieces after data cleaning. Examples of data cleaning include, but are not limited to:

- converting mixed text/numerical values to purely numerical values (e.g., “120VAC” replaced with 120 for voltage, “6.25A” replaced with 6.25 for current (amps)),
- converting equipment acquisition values to 2024 values based on inflation rates, and
- treatment of missing data (e.g., weight, voltage, current) – equipment lacking essential data are omitted from the study.

The functional unit for each piece of equipment is expressed as the operation of the equipment over its anticipated lifespan; accordingly, the reference flow is defined as one piece of equipment. The system boundary includes the production, distribution, use, and end-of-life stages of the equipment life cycle (Fig 6). As an LCA study, the impact assessment (section 4.3) covers multiple environmental issues, including climate change, acidification, eutrophication, smog formation, and human and ecological toxicity.

Given the practical infeasibility of conducting LCAs for thousands of pieces of equipment, it is necessary to prioritize the equipment with the highest environmental impacts. The problem, of course, is that the environmental impacts cannot be known until the LCAs are done. Hence, some form of predictive screening is needed. This is where EEIO approaches can be applied, i.e., by grouping “similar” pieces of equipment into expenditure categories, each with a corresponding emissions factor. As discussed in section 3, this approach has major shortcomings, including its high level of aggregation and incomplete coverage of the equipment life cycle.

We developed a novel approach to screening equipment based on environmental and economic criteria, as elaborated in section 4.2.

## 5.2. Life cycle inventory analysis

Our screening approach is aimed at providing a first estimate of the environmental impacts in each life cycle stage for each piece of equipment. For this initial screening, GHG emissions are the only indicator of environmental impacts. This limitation of our approach reflects gaps in data availability, particularly for complex equipment that has not been previously studied from an LCA perspective.

For the production stage, we grouped the equipment using the United Nations Standard Product and Services Codes (UNSPSC) taxonomy [33]. The UNSPSC comprises four levels of classification of goods and services across the

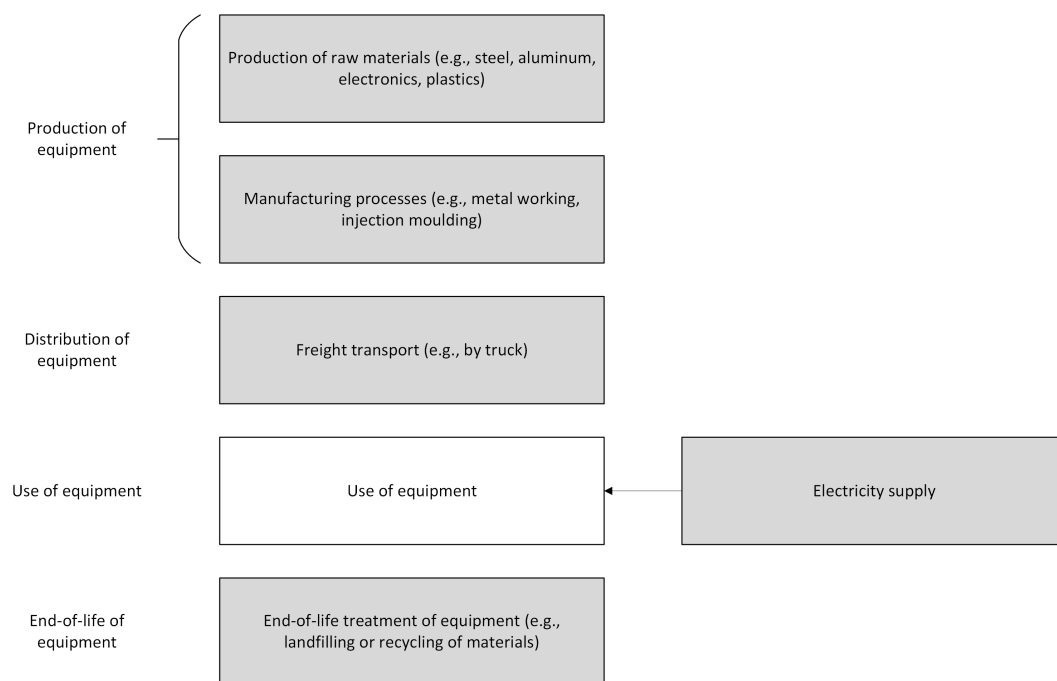


**Fig 6. System boundary for LCAs of laboratory and scientific equipment.** Shaded boxes represent processes with background data from the ecoinvent database.

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economy; in order of increasing granularity, the levels are: segments, families, classes, and commodities. Our grouping of equipment is done at multiple levels to strike a balance between limiting the groupings to a manageable number (i.e., as using more granular levels of classification increases the number of groups) while keeping the groups relatively homogeneous (i.e., as more aggregated levels of the UNSPSC have more heterogeneity within each group). In some cases, we make our own grouping of similar UNSPSC classifications (e.g., combining UNSPSC codes for domestic freezers, domestic refrigerators, and industrial refrigerators into a single group of refrigerators and freezers).

For each group, an LCA proxy product is selected, either from ecoinvent (a widely used global LCA database containing granular data on thousands of materials and industrial processes [34,35]), or, if no suitable proxy is found in the database, from academic or other literature sources. In total, there are 32 proxies from ecoinvent and four proxies from other sources. The proxy for each equipment group applies to each piece of equipment in the group. The GHG emissions of each proxy are calculated per unit of mass and multiplied by the mass of each piece of equipment. The results are then divided by the equipment life expectancy, such that the emissions from the production of each piece of equipment are expressed on an annualized basis. Table 1 provides an illustrative example of this approach.

The distribution stage was omitted from the screening calculations given that previous LCA experience has found it to be a minor contributor to life cycle environmental impacts [30] – as reinforced by our subsequent LCAs of high-impact equipment.

For the use stage, the power consumption of each piece of equipment is multiplied by the total number of hours per year for which the equipment is in operation, calculated from the equipment usage frequency (hours per day and days per week) according to Laboratories Canada. The GHG emissions from electricity use are calculated using ecoinvent data for the electricity supply mix where the equipment is located.

For the end-of-life stage, estimates of GHG emissions from end-of-life treatment processes are made for each LCA proxy used for modelling the production stage. Some proxies from ecoinvent (e.g., refrigerators) include data on the end-of-life stage. In other cases, end-of-life emissions are estimated using assumptions about the material composition of the equipment (i.e., approximate proportions by mass of steel, aluminum, and other materials) combined with estimates of the emissions attributable to recycling of materials, per unit of mass [24]. As with the production stage, the emissions from the end-of-life stage are annualized by the equipment life expectancy.

The annualized life cycle GHG emissions for each equipment category are calculated as the sum of the annualized production, use, and end-of-life emissions for each piece of equipment in the category. Across all 3470 pieces of equipment, the following equipment categories were selected for contributing 1% or more to the total annualized life cycle emissions:

- pumps,
- compressors,
- refrigerators and freezers,
- chromatography systems,

**Table 1. Example of screening approach for production stage.**

| Equipment description                                 | Laboratory refrigerator |
|-------------------------------------------------------|-------------------------|
| Life expectancy (years)                               | 10                      |
| Equipment mass (kg)                                   | 211                     |
| LCA proxy                                             | ecoinvent: refrigerator |
| LCA proxy mass (kg)                                   | 60                      |
| LCA proxy GHG emissions (kg CO <sub>2</sub> eq./kg)   | 4.52                    |
| LCA result GHG emissions (t CO <sub>2</sub> eq./year) | 0.1                     |

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- spectrometry systems, and
- carbon dioxide incubators.

The categories of furnaces and scanning electron microscopes were added based on economic criteria; these equipment categories account for more than 2% of the total economic value (acquisition value, expressed in 2024 dollars) across all 3470 pieces of equipment. Chromatography systems were omitted due to limited data; available information for gas chromatography systems [36] uses aggregated EEIO-based data and is limited to GHG emissions, while available data for liquid chromatography systems, from a single manufacturer [37], is also limited to GHG emissions and is more than 10 years old. Regarding spectrometry systems, a major manufacturer of mass spectrometers has published environmental data [38], but again the data are limited to GHG emissions and cover only the production stage of the equipment life cycle. Furnaces were omitted given their similarity to equipment used in other industries and the fact that they have a predictable life cycle profile (i.e., use-intensive) based on previous LCA experience [24,25]. In contrast, scanning electron microscopes stand out as specialized, complex pieces of equipment that could have a different life cycle profile – as found in our LCA results.

Our LCAs of the selected equipment combine foreground data and parameters (i.e., regarding equipment mass, power consumption, usage frequency, and life expectancy) with background data (i.e., regarding material production and manufacturing processes, distribution, electricity supply for equipment operation, and end-of-life treatment of equipment). As outlined in Tables 2 and 3, foreground data are sourced from Laboratories Canada, or from equipment manufacturers where available, and background data are sourced from the ecoinvent database. Further details are provided in S1 File.

**Table 2. Foreground data and parameters for selected high-impact equipment (details in S1 File).**

| Equipment                     | Mass per piece (kg) | Power consumption per piece (kW) | Usage frequency low/ average/ high (hours/year) | Life expectancy (years) |
|-------------------------------|---------------------|----------------------------------|-------------------------------------------------|-------------------------|
| Pumps                         | 2.5                 | 0.04                             | 52/ 966/ -                                      | 10                      |
| Compressors                   | 140                 | 4.0                              | 520/ -/ -                                       | 15                      |
| Refrigerators and freezers    | –                   | 0.5                              | Continuous                                      | 10                      |
| Carbon dioxide incubators     | 118                 | 1.1                              | 130/ continuous                                 | 15                      |
| Scanning electron microscopes | 1000                | 1.2                              | -/ 520/ 2912                                    | 15                      |

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**Table 3. Background data sources (details in S1 File).**

| Equipment                     | Production                                                  | Distribution                             | Use                                                                                  | End-of-life                                                      |
|-------------------------------|-------------------------------------------------------------|------------------------------------------|--------------------------------------------------------------------------------------|------------------------------------------------------------------|
| Pumps                         | ecoinvent production process                                | ecoinvent truck freight process          | ecoinvent electricity supply process                                                 | Included in ecoinvent production process                         |
| Compressors                   | ecoinvent production process                                | ecoinvent truck freight process          | ecoinvent electricity supply process                                                 | Included in ecoinvent production process                         |
| Refrigerators and freezers    | ecoinvent production process                                | Included in ecoinvent production process | ecoinvent electricity supply process                                                 | Included in ecoinvent production process                         |
| Carbon dioxide incubators     | ecoinvent refrigerator production process, scaled by mass   | Included in ecoinvent production process | ecoinvent electricity supply process<br>ecoinvent CO <sub>2</sub> production process | Included in ecoinvent production process                         |
| Scanning electron microscopes | ecoinvent production processes for materials and components | ecoinvent truck freight process          | ecoinvent electricity supply process                                                 | ecoinvent waste treatment processes for materials and components |

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### 5.3. Life cycle impact assessment

Life cycle impact assessment of selected high-impact equipment (i.e., after the screening step) was conducted using the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) 2.1 method [39,40] in OpenLCA software, version 2.5.0. The TRACI method, although not without its own limitations (see below), is most relevant in the Canadian context and supports results for 10 environmental indicators:

- global warming potential, expressed as a mass of CO<sub>2</sub> equivalent emissions,
- acidification potential, expressed as a mass of SO<sub>2</sub> equivalent emissions,
- eutrophication potential, expressed as a mass of N equivalent emissions,
- smog formation potential, expressed as a mass of O<sub>3</sub> equivalent emissions,
- particulate matter formation, expressed as a mass of PM<sub>2.5</sub> equivalent emissions,
- stratospheric ozone depletion potential, expressed as a mass of CFC-11 equivalent emissions,
- carcinogenic effects to humans, expressed as comparative toxic units for humans (CTUh),
- other human toxicological effects, expressed as CTUh,
- ecotoxicological effects, expressed as comparative toxic units for ecosystems (CTUe), and
- fossil fuel resource depletion, expressed as MJ equivalent.

We omit the fossil fuel depletion indicator because it arguably represents more of an economic than an environmental issue, and the methodology of “resource depletion” assessments, along with the interpretation of resulting indicators, is contested [41–44]. We also omit stratospheric ozone depletion potential. Given that ozone depleting substances have been phased out by the Montreal Protocol and that the ozone layer shows signs of recovery, some LCA experts have questioned the relevance of this impact category altogether [45–47]. Moreover, LCA databases have not kept pace with the phase-out of ozone depleting substances [47]. These and other limitations have led to the conclusion that “... currently available LCA ozone depletion practices are unsuitable for supporting decision-making” [47].

### 5.4. Life cycle interpretation

Given that the goal of this study is to inform measures to reduce environmental impacts in the procurement and operation of laboratory and scientific equipment (section 4.1), our interpretation of LCA results includes contribution analysis to high-light environmental “hotspots” in the equipment life cycle, along with scenario analysis of the equipment usage frequency. Usage frequency scenarios reflect the minimum and maximum usage frequency for each equipment group based on data from Laboratories Canada (Table 2).

### 5.5. Artificial intelligence tools used in manuscript revision

AI tools, particularly Chat GPT, were used in revising this manuscript to address reviewer and editor comments. Chat GPT was used to find literature references on sustainability transformations and to connect our LCA results to this literature. Suggestions from Chat GPT were verified and modified by the authors, who accept full responsibility for this work.

## Supporting information

**S1 File. LCA data and calculations.**  
(XLSX)

**S2 File. LCA results for pumps.**

(XLSX)

**S3 File. LCA results for compressors.**

(XLSX)

**S4 File. LCA results for refrigerators and freezers.**

(XLSX)

**S5 File. LCA results for carbon dioxide incubators.**

(XLSX)

**S6 File. LCA results for scanning electron microscopes.**

(XLSX)

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**Visualization:** Alexander Cimprich, Sahand Kasaeipour.

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**Writing – review & editing:** Alexander Cimprich, Sahand Kasaeipour, Steven B. Young.

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