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Lab sustainability programs LEAF and My Green Lab®: impact, user experience & suitability†

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Facing the climate crisis and planetary boundaries, research institutions must address the challenge of becoming climate-neutral and using resources more sustainably. Natural science laboratories are the most resource-intensive and CO_2-emitting units within these institutions. Consequently, research groups aim to understand how to lower emissions and become sustainable by participating in green lab programs for wet labs, such as My Green Lab® or LEAF. Here, we compare these programs, analyse their impact on emission savings, and give insights from conducting both programs simultaneously in our biological and chemical labs. As a centrepiece, we provide a quantitative comparison of the programs based on a Germany-wide survey of participants from both programs. We showcase the significant impact of the programs on employees' motivation to work sustainably, highlight the advantages and shortcomings of the programs, and elucidate the pitfalls of greenwashing risks and the risks of leaving the most effective measures unimplemented. Finally, we provide decision-making guidance to help scientists choose the most suitable lab sustainability program based on their individual research backgrounds, needs, and personal preferences.

Sustainability spotlight

Scientific research is extremely resource-intensive, and science is far from being a sustainable sector: if science were a country, it would be number 40 in CO_2 emissions. Similarly, research laboratories produce enormous amounts of waste. Our aim is to ease the process for labs to make use of sustainable lab programs and to make an educated choice of which one to use. Sustainable lab programs address SDGs 3 and 6 by reducing (chemical) pollution and by promoting the responsible use of water as a resource, SDG 7 by enhancing energy efficiency, SDG 9 by improving sustainable industrialization, SDG 12 by offering solutions for responsible consumption of laboratory consumables and equipment and, importantly, SDG 13 by reducing CO_2 emissions.

1 Introduction

The climate crisis and the pollution of the environment are some of the greatest threats to the livelihoods of current and future generations.[1,2] Increase of water shortages, even droughts, and subsequent famines, as well as other weather extremes and biodiversity loss, must be fought by drastically reducing greenhouse gas emissions, achieving climate neutrality, and limiting global warming to 1.5 °C.[3] Even though scientific research drives innovation and helps to understand both climate change and planetary boundaries, research itself is very resource-intensive. If clinical research were a country, it would be number 40 in CO_2 emissions.[4] Lab spaces consume five to ten times more energy and three to five times more water[5] than office buildings. Reaching climate-neutrality goals such as those mandated by the EU until 2050,[6] by the German Federal Government until 2045,[7] or by the State of Baden-Württemberg until 2030 (ref. 8) remains ambitious given the circumstances. Similarly, plastic waste has become a global environmental problem by its end-of-life as litter, in land-fill or incineration.[9] Labs produce 5.5 Miot of plastic waste annually, which is almost 2% of the world's total plastic waste.[10] Over their life cycle, plastics contribute 3.5% to the total global CO_2 emissions.[11]

Fortunately, funding agencies such as the German Research Foundation (DFG), the Science Foundation Ireland (SFI), the Medical Research Council (MRC), the Marie Skłodowska-Curie Actions, the Wellcome Trust, and Cancer Research UK[12–17] have started to demand that the implementation of sustainable lab practices has to be addressed in research proposals and that these measures are then implemented in the projects funded by them. Moreover, scientific publishers, by launching sustainability-related journals (including *RSC Sustainability*, *Green Chemistry*, *MDPI Sustainability*, and *Nature Sustainability*), and scientists themselves are becoming aware of the environmental impact of research and aim to make science in general and wet labs in particular more ecologically sustainable.

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However, many scientists ask themselves where to start. Typically, research labs do not have the capacity to find out the most sustainable alternatives for specific processes or to identify the biggest consumers of energy and other resources by themselves. Thus, research groups can decide to participate in programs specifically designed to make research in wet labs more sustainable, to understand the jungle of (silent) consumers, and to give guidance on where to save resources most effectively. Research labs find themselves faced with quite some options to choose from. Over 51 sustainable lab programs – of which many are institution-bound – help guide the way with more or less extensive suggestions on how a lab can become greener.[18]

The two market-leading sustainable lab programs are the US-American NGO program My Green Lab® (MGL)[19] and the British program LEAF (Laboratory Efficiency Assessment Framework)[20] from the University College London. These programs do not only offer suggestions on how to improve wet lab sustainability but also supply users with additional resources such as publications on the environmental impact of freezers or on the use of glass-ware *vs.* single-use plastic articles,[21,22] calculators for CO_2 emissions and financial savings, explanation videos, and consumer guides, to name a few. To increase comparability among labs, honour the efforts taken by staff members, and fulfil funding agencies' sustainability requirements,[12,13,15] the programs offer certification for lab sustainability. Both programs work in a remote manner, *i.e.*, labs implement proposed measures, more or less adapted to their specific research, and receive certification without external validation. However, which program should one choose? To date, there is only detailed reporting on one of the programs,[23,24] and a description of the programs without peer review,[16] but no scientific quantitative comparison has been done on them.

Here, we review and compare My Green Lab® and LEAF first in terms of publicly available information, and second, investigate how they perform in practice. As a case study, we executed both programs in our lab to get explorative first-hand insight, find out about savings potential, and experience general practicability. As the centrepiece of our study, we performed a Germany-wide survey to obtain quantitative and statistically reliable data on user experience from 59 individuals of labs in different research fields, covering feedback from 15 of all 19 institutions where one of the two programs has been implemented. In the survey, we found no significant difference in overall program rating. Both are widely rated ‘good’ and to ‘highly’ increase sustainability and motivation to work sustainably in the lab. However, according to individual differences such as research background or staff type, users do show preferences for one program or the other. Furthermore, we summarise the programs' theoretical and practical impact, key advantages, and weak points, investigate greenwashing risks, provide a decision-making facilitator, and present additional elements users could take up from on-site inspection by commercial lab sustainability consultancies to address common challenges that users of the programs faced during their implementation.

2 Results & discussion

2.1 Comparison of LEAF and My Green Lab® – publicly available information

2.1.1 Design of program/overview and certification process. LEAF[20] (Laboratory Efficiency Assessment Framework) consists of 48 proposed measures to implement sustainability in natural science laboratories. Usually, one or two lab members per research group are responsible for implementing or delegating the implementation of measures and filling out the web browser-based LEAF catalogue in free text. The topics covered are energy, waste, water, people, research quality, purchasing, equipment, IT, sample and chemical management, teaching, and ventilation. Usually, within some months to a year, users implement 16 fixed criteria for the Bronze level and another 17 and 15 criteria for the Silver and Gold levels, respectively (Fig. 1a). The LEAF system seeks to increase exchange and share best practices between labs and to avoid greenwashing by asking labs to cross-audit each other for certification after the implementation period. LEAF certification is valid for one year. In addition, LEAF offers savings calculators that allow for the approximate evaluation of cost and CO_2 savings that could be achieved. If labs use the calculators, an institution/lab report of monetary and emission savings can be generated automatically (*c.f.* Table 1).

My Green Lab®[19] (MGL) presents users with applicable topics based on their lab's background in up to 15 pages of a multiple-choice questionnaire on sustainable behaviour and measures in laboratories (Fig. 1b). At least 50% of lab members participate in the baseline assessment, which is a multiple-choice questionnaire to understand users' education on sustainable practices and to evaluate the measures already implemented in their lab. Covered topics are community, waste, resource management, purchase, green chemistry, water, plug load, fume hoods, cold storage, large equipment, infrastructure energy, fieldwork, animal research, and travel. By averaging answers from users across all topics, labs gain a score that is the ‘baseline assessment’. Labs are provided with feedback on how to improve based on the answers given. Labs should implement suggested measures within the following 6–9 months and then repeat the assessment. If they score above 40%, they receive the first certification level, Bronze. Higher certification (Silver, Gold, Platinum) is achieved in incremental steps of 10 percentage points up to 80%, the ‘Green’ level certificate. Certification is valid for two years. My Green Lab® offers additional programs (*c.f.* Table 1) such as the Freezer Challenge (see below, ‘Impact of the programs’), the ACT label (Accountability, Consistency, and Transparency) on the sustainability of consumables and equipment, and the ambassador program (free training including subsequent certification possibility as a sustainability ambassador and Microsoft Teams exchange platform).

2.1.2 Impact of the programs. LEAF, launched in 2017 as a pilot program at UCL (University College London), is Europe's first academic lab sustainability certification program open to all academic institutions. In its piloting period from 2018–2020, 235 laboratory groups from 23 institutions across the UK and

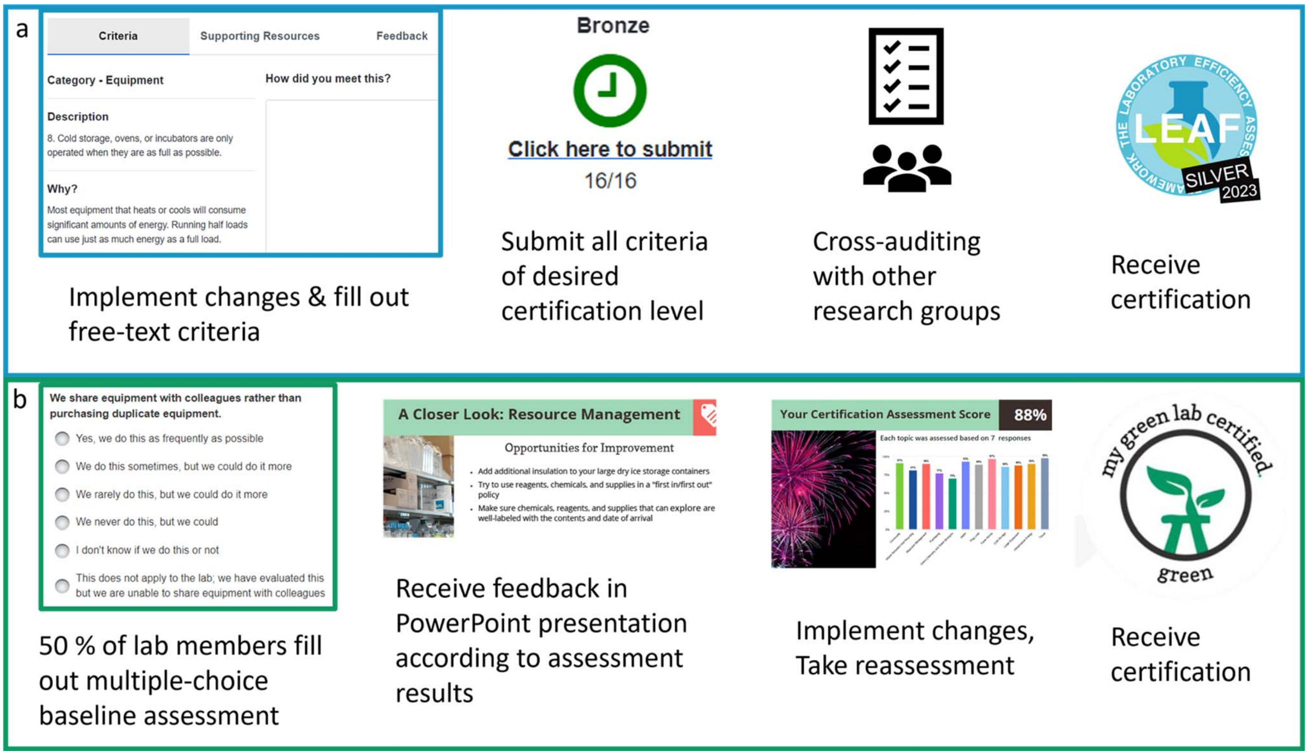

Fig. 1 Design and certification process of (a) LEAF and (b) My Green Lab®. Screenshots and logos reproduced with permission from MGL and LEAF.

Ireland stated average savings of 2.9 tonnes of carbon dioxide equivalent (tCO_2e) and £3700 per year, of which 70% were energy savings (total 648 tCO_2e).[25] By July 2024, LEAF has ~3860 labs participating from 115 institutions and 15 countries.[26,27] LEAF has gained a particularly high impact with the UK's Medical Research Council (MRC) announcing in its strategic delivery plan 2025 to "target 'gold' status for our organisations in the LEAF scheme".[14] One of LEAF's strengths is its embedding in academia. Martin Farley, former Sustainable Research Manager at UCL and LEAF inventor, has been continuously publishing scientific data on sustainable alternatives for laboratories.[21,22,28,29] As scientists rely on scientific data, they also need scientific proof when it comes to, *e.g.*, alternative sample storage/freezer maintenance, emissions of their research, and actual savings/comparisons to alternatives, which LEAF provides in the form of publications, monetary and CO_2 emission savings calculators for different actions in their platform and a guidebook on more sustainable purchase. LEAF has announced future plans, including education and training modules, an online forum, and site-specific support.[27]

My Green Lab® is a 20-person non-profit organisation founded in 2013. By 2024, MGL has certified >2900 labs from 46 countries[30] and has reached increasingly high impact, exemplified by the fact that it was named to be one of the key elements in the United Nations Race to Zero in halving science's carbon footprint by 2030.[31] One of the most impactful programs by MGL is the public Freezer Challenge. Participating labs from all over the world enter the number of differently optimised ultralow-temperature freezers. According to MGL, since 2017, this has saved 76.5 million kW h.[32] The 2024 Freezer Challenge alone resulted in 31.8 million kW h of energy savings or 22 000 tCO_2e being avoided and engaged more than 3100 labs from 35 countries.[32] MGL has launched the ACT (Accountability, Consistency and Transparency) program, an eco-label making the emissions of products transparent and comparable and pushing companies to invest in greener products and life cycle assessments for their products. MGL provides additional supporting tools such as the exchange platform 'Ambassadors' and continuously publishes new educational material (blog, podcast, summits). MGL supplies extra training in the form of the 'Accredited Professional Modules' (additional fees, approved training course by RSC).[33] To date, there are no savings per lab being calculated, but numbers are available from a case study (Colorado Dept. of Agriculture, energy savings 187 000 kW h year)[34] and estimations from Astra Zeneca's savings (900 tCO_2e, and energy savings of \$317548).[34] MGL has stated to build an 'Impact Estimator'[18] to fill this gap and investigated carbon footprint in their report 'The Carbon Impact of Biotech & Pharma'.[35]

Whereas the impact in terms of savings across labs can vary greatly, we here show the possible impact when following all advice. In an extensive study of 105 laboratories in France, Paepe *et al.* showed that the carbon footprint in research is dominated by either electricity or purchase, depending on the institution's location.[36] Therefore, we check how the carbon emissions of these two highest-impact topics can be reduced by

Table 1 Overview and comparison of LEAF and My Green Lab® specifications

LEAF	My Green Lab®
Investment (monetary and time)	
£1100–2600/institution, depending on employee count: <1000: £1100, <2000: £1600, <3000: £2000, 3000+: £2600	Academic labs: 500–350 US$ per laboratory, *i.e.*, research group, price banding: > 5 labs: $475, >10: $450, >24: $400, 50+: $350
Only available for academic labs, a commercial version is planned	Commercial labs: $4000–$2800 (1–50+ labs)
At least one person in the lab	At least 50% of lab members
20–40 min (Bronze, depending on the knowledge of the person filling in the form), free text	Per lab member ~40 min for baseline and certification assessment each, multiple choice
Covered topics	
Waste	Waste
Water	Water
Purchasing	Purchasing
People (includes travel)	Community
	Travel
Equipment (includes MGL equivalent topics) IT	Plug load, cold storage, large equipment (includes IT)
Sample and chemical management (includes green chemistry)	Resource management
	Green chemistry
Ventilation (includes heating)	Fume hoods, infrastructure energy
Equivalents of infrastructure energy such as lighting and heating are included in categories ventilation and equipment	
Research quality	—
Teaching	—
—	Field work
—	Animal research
Resources	
Tips for all criteria in web-tool	PowerPoint presentation with tips on how to improve sustainability, adjusted to the result from baseline assessment
Administrators can add local tips	No local adaptation possible
CO_2 and cost calculator	—
Guide how to audit	—
—	Freezer challenge
—	Ambassador program (exchange platform)
—	Accredited professional program (training platform; extra fee)
Consumables' guidebook	ACT label (consumables' & devices' label on their carbon impact, transparency on production, packaging, shipping)
Online resources (scientific publications, videos, posters, stickers)	Online resources (scientific publications, videos, posters, stickers)
Institutional reports	Action tracker (excel sheet)
No third-party verification available	Third-party verification through 'impact laboratories' as a subsidiary of MGL
Process of implementation	
Web tool with all criteria, tips and publications	Multiple-choice baseline assessment sent to user as links, PowerPoint presentation with tips and links to more resources according to baseline result
Individual progress trackable in the web tool	Individual progress trackable in a Microsoft excel sheet 'action tracker'
Institution administrator sets up labs and lab members in the web tool	Set-up carried out by MGL
Prioritisation of criteria given by the levels: 16 criteria for Bronze, 17 criteria for Silver, and 15 criteria for Gold	No prioritisation of criteria; the prioritisation/implementation process is up to the user
Tips for each criterion, no adaptation to specific lab or institution; the administrator can enter (local) specific tips	Tips specific to assessment
Timeline	
Self-determined; recommendation: first year to implement measures for the Bronze criteria (or higher), submission of fulfilled criteria, audit by another research group, certification	Self-determined; recommendation: 3–6 weeks for the baseline assessment, feedback from MGL on what to implement in a PowerPoint presentation, 6–8 months to implement measures, certification assessment

Table 1 (*Contd.*)

LEAF	My Green Lab®
Certification/transparency	
3 levels (Bronze, Silver, Gold)	5 levels (Bronze, Silver, Gold, Platinum, Green)
Fixed criteria to reach a level, compensation across criteria of a level not possible	All criteria weigh equally, and the percentage of criteria met leads to the score
"Does not apply" is possible with justification	"Does not apply" is possible; justification is not required
Audit by other research group/sustainability officer of the institution	No external verification, MGL states to carry out spot checks in case of suspicion of misuse
Calculator to estimate CO_2 and cost savings; it allows entering own costs per kW h and CO_2 emissions for energy mix	No CO_2 or savings calculator available
Recertification required each year	Recertification required every second year
Transferability to Germany/other countries	
Designed for british laboratories (closer to German/EU standards)	Designed for US laboratories (some criteria not adjusted to German standards, *e.g.*, legal regulations)
English only	Multiple languages available, translation sometimes poor
Scalability & intra-institutional collaboration	
Beneficial if many labs within an institution participate (cross-auditing); pricing is independent of the number of labs from one institution	Some measures encourage exchange with other participating labs/stakeholders, pricing per lab
Intra-institutional collaboration is intrinsically built into the program	Intra-institutional collaboration is encouraged

following LEAF and MGL's advice. For locations with high CO_2 emissions per electricity production unit, electricity has the highest carbon footprint in research.[36] Literature review reveals that 25–70% of a lab building's electricity consumption is needed for ventilation,[37–39] the remaining part is mostly consumed by infrastructure such as lighting and plug load equipment. The highest impact achievable through MGL and LEAF is to follow their advice on optimising fume hood usage and ventilation rates. LEAF and MGL advise best practices for fume hood usage, *e.g.*, closing fume hoods, which results in annual savings of 5–25% of the ventilation system.[40] Both programs suggest a reduction in ventilation rates. Night-time setbacks can reduce ventilation energy consumption by 25%, and different scenarios of reducing air change rates during operating hours could reduce consumption by up to 58%.[40] LEAF asks for a 'reduction of ventilation rates' as a gold criterion and does not differentiate between night-time setbacks and reductions during operating hours. MGL differentiates between these, but both are not obligatory.

Further high electricity consumers are lighting, large equipment, particularly cold storage equipment, and other heating and cooling equipment. Both programs ask for ways to ensure light is turned off when not needed and to replace incandescent light sources with LEDs. This can lead to savings of up to 85%.[41] LEAF and MGL address equipment usage with slight differences, but both programs focus on big consumers, especially ultra-low temperature freezers (~30% of plug-load energy consumption).[42] They propose impactful measures like a 10 °C temperature increase for ultra-low temperature freezers from −80 °C to −70 °C (up to 30% savings per freezer)[28] and proper maintenance (~25% savings).[43] Further proposed measures include fully loading other large equipment when running it, setting up systems to ensure turn-off, regular maintenance of specific devices, *etc.*

Purchase was shown to have the first or second-highest carbon impact of research laboratories, depending on the lab's location.[36] Optimising purchase and waste reduction is addressed in both programs through multiple criteria encouraging the reuse of single-use plastic-ware, second life of devices, sustainable purchase, and optimised use and recycling of solvents. Additionally, LEAF has a sustainable consumables guide. MGL has created the ACT label that certifies consumables as greener alternatives to conventional products. Users get an overview of shipping impact, green energy for production, *etc.* The continuously growing database also pushes manufacturers to greener production and more transparency on emissions.

2.2 Comparison in practice

While publicly available information only gives a theoretical idea of the programs and might be biased, we performed a reality check for both programs. For explorative insight, we conducted both programs in our lab. For a more objective understanding of the programs' strengths and weaknesses under diverse, real conditions, we performed a survey collecting user experience among labs throughout Germany.[44] We sent out our survey to all LEAF institution administrators, while MGL distributed the survey to all labs participating in MGL in Germany. We received feedback from 24 LEAF and 35 MGL participants. For further details, *e.g.*, on participant acquisition, see Methods.

2.2.1 Impact in practice. In our lab, we performed both MGL and LEAF simultaneously, and with efforts taken so far, we could reach 'Green' in MGL (highest level) but only 'Silver' in LEAF (medium level). A major goal of MGL is the education of lab members and creating awareness among users, which clearly happened while going through MGL certification, as at least 50% of lab members are involved in the assessments. The fact that we reached the MGL 'Green' level indicates that we have successfully educated our lab members on sustainable behaviour, green chemistry, reuse of articles, optimised recycling of packaging, water use, freezer maintenance, *etc.* In LEAF, one or two persons usually take care of most issues. Thus, unless sustainable lab practices are on the agenda of lab meetings and regularly discussed within the research group, other lab members might not be aware of many measures taken.

A limitation of MGL became evident here: several significant challenges may remain to be resolved even after reaching the highest certification level, 'Green'. At the time of certification, we had not yet implemented night-time setbacks in our lab, nor did we reduce air ventilation rates, and the purchase was only partly optimised. For many labs, we fear this might prevent the exchange with estates to reduce ventilation rates, to optimise (central) purchase, or to give a 2nd life to lab equipment, which are obligatory criteria in the LEAF Gold level.

2.2.2 Motivation and sustainability increase. When implementing the programs simultaneously in our lab, we noticed an increased awareness among lab members of the need to drive change and improve certain practices more sustainably. The survey results further validated this finding. Users' motivation to work sustainably in the lab significantly increased with the introduction of a lab sustainability program (Fig. 2a, mean values after *vs.* before program introduction: increase $\text{mean}_{\text{LEAF}} = +0.79$, increase $\text{mean}_{\text{MGL}} = +0.4$. Wilcoxon-test, $p_{\text{LEAF}} < 0.001$, $p_{\text{MGL}} = 0.001$, $n_{\text{LEAF}} = 24$, $n_{\text{MGL}} = 33$). Regardless of the initial interest in sustainability, 62% of participants answered that it would make them very satisfied, and 29% would be rather satisfied to work in a lab that is certified as a sustainable lab.

On average, participants found the programs 'good' ($\text{mean}_{\text{LEAF}} = 3.04$, $\text{mean}_{\text{MGL}} = 2.93$, scale 0–4, very bad to very good. Bootstrap-test, $p = 0.667$). There was no significant difference observed between the programs. However, we saw a trend of chemists preferring LEAF over My Green Lab® by 0.53 (scale 0–4, very bad to very good. Bootstrap-test, $p_{\text{chemistry}} = 0.233$, $p_{\text{biology}} = 0.639$. $n_{\text{LEAF–chemistry}} = 6$, $n_{\text{MGL–chemistry}} = 5$, $n_{\text{LEAF–biology}} = 15$, $n_{\text{MGL–biology}} = 26$, Fig. 2b).

Thanks to the programs, users rated lab sustainability to 'highly increase' ($\text{mean}_{\text{LEAF}} = 3.04$, $\text{mean}_{\text{MGL}} = 3.12$, scale 0–4, no to very high increase. Bootstrap-test, $p = 0.763$), and we observed no significant difference between programs in this question (Fig. 2c).

Both programs require users to implement a subset of organisational improvements that foster best practices. These include freezer, sample, and chemical management, shared protocols, reliable data storage, and lab management software. As a result, survey participants reported that the program improved at least two of four aspects outside sustainability. This improvement (in the order of prevalence of occurrence: organisation in lab, processes, safety, teambuilding, *c.f.* ESI, Fig. S1†) can even enhance the quality of research.

2.2.3 Programs' resources. Both programs provide additional resources. These include scientific publications on green lab actions and their impact, references to best practice examples, and explanatory videos, posters, stickers, and support from program management. LEAF provides a cost and CO_2 emission calculator. MGL supplies extra training, the 'Accredited Professional Modules' (additional fees, approved training course by RSC, listed on RSC database[33]) and a free exchange 'ambassador' platform with regular meetings and input. LEAF additionally offers a consumables guide; My Green Lab® offers the ACT label, which allows consumers to make a greener choice for products (see more in 'Impact in practice').

Both programs' resources were equally liked by the users ($\text{mean}_{\text{LEAF}} = 3.04$, $\text{mean}_{\text{MGL}} = 2.94$, scale 0–4, not at all to very much. Bootstrap-test, $p = 0.273$, see Fig. 2d, for more detail, see Table 2).

2.2.4 User-friendliness. LEAF uses a web browser platform. The internal institution administrator coordinates new labs and members, certification submissions, and audits between groups without needing external support. The lab member(s) responsible for LEAF enter how they address criteria in free text format. Supporting resources, references and local guidance (entered by the institution's administrator) are available at the same location. Users see their progress continuously. Optional calculators for cost and emission savings give an approximate evaluation of the impact of certain measures (*e.g.*, freezer maintenance).

MGL uses a browser-based multiple-choice questionnaire. Aspects not generally known to users are easily comprehensible with mouse-over functions. My Green Lab® provides the results from the baseline assessment, feedback, and suggestions in a Microsoft PowerPoint presentation sorted by topic, together with an introduction to each topic's impact. My Green Lab® offers an Excel sheet 'action tracker' but no online tool or prioritisation.

From the survey, we saw that users on average 'liked' structural aspects of both programs ($\text{mean}_{\text{LEAF}} = 2.89$, $\text{mean}_{\text{MGL}} = 2.82$, scale 0–4, not at all – very much. Bootstrap-test, $p = 0.742$, Fig. 2e), including the documentation of implemented measures, the clarity to fill out LEAF's browser-based catalogue/MGL's questionnaire, transparency and the structure in general. Specific criticism of the structure mentioned in the comments section was the lack of clarity on navigating the LEAF web tool and the use of calculators and filling out the MGL assessment.

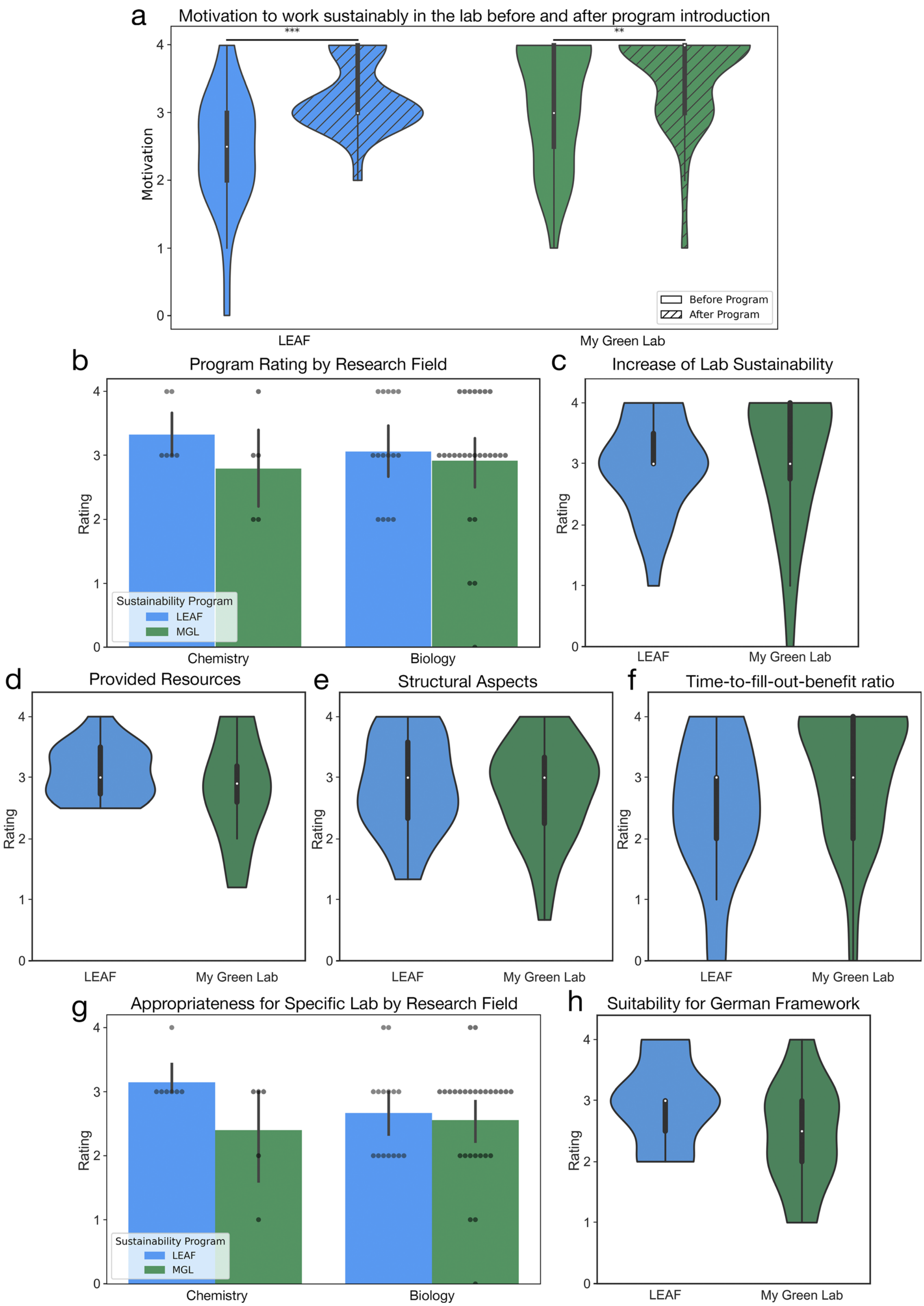

Fig. 2 Rating of LEAF and MGL from survey participants. (a) Motivation to work sustainably in the lab before and after participation in a lab sustainability program. (b) Average overall program rating by discipline. (c) Perceived increase in laboratory sustainability. (d) Rating of the resources provided by the program. (e) Rating of structural aspects of the programs. (f) Rating of input–output ratio; the time to fill out either LEAF's web-tool or MGL's baseline/certification assessment *vs.* the gained value. (g) Rating of the appropriateness of the programs for the specific research field. (h) Rating of the appropriateness of the programs for the German framework. Violin plots visually represent the distribution of answers, with thick bars indicating the interquartile range (IQR), thin black bars indicating 1.5x IQR, and white dots representing the median. Bar plots show mean values, with 95% confidence intervals indicated by bars, and individual data points shown as dots. Bar plots were used when the sample size was less than 10. Plots display participants' ratings of the program on different aspects on a scale from 0 = '(liked) not at all/very low' to 4 = '(liked) very much/very high'.

Table 2 Mean values of multiple survey questions were pooled into one umbrella value. Column names represent the umbrella values that were compared between programs. Column entries are the subquestions that were pooled

Quality of resources	Structural aspects of program	Improvements outside sustainability
Quality resources	Program structure	Processes
Quality videos	Transparency of program	Safety
Quality ACT label	Clarity filling out	Organizational structure
Support by program management	Documentation of implemented measures	Team building
Support during implementation		

Similarly, the time needed to fill out the program's web tools in relation to the achieved benefits was rated good for both programs ($\text{mean}_{\text{LEAF}} = 2.52$, $\text{mean}_{\text{MGL}} = 3.12$), with My Green Lab® receiving a significantly better score (Bootstrap-test, $p < 0.05$, see Fig. 2f). In our research group, we assessed the time-to-fill-out; not comprising any implementation steps. We found an average time of 38 minutes to fill out one MGL assessment ($n = 3$). *I.e.*, certification level-independent, the pure time it takes to fill out baseline and certification assessment is ~73 minutes per person. For the Bronze level in LEAF, it took users 27 minutes on average ($n = 2$) to fill out the criteria. As all three certification levels contain similar numbers of criteria, we assume an equal amount of time per level.

2.2.5 Level of detail of criteria. LEAF criteria mostly group measures in categories, *e.g.*, asking for optimised use of several devices at once (*i.e.*, 'There is a system in place to ensure [certain workflow is optimised]'). My Green Lab® asks for very specific details on particular devices to be fulfilled (*e.g.*, 'We unplug/turn off [certain device] when not in use'). However, about half of MGL users found the criteria to be not detailed enough, while half the users found the depth of the criteria just right. From the comments section of three users, we consider the reason for this opposing result to possibly derive from users finding criteria not helpful, specific, or solution-oriented and that they would have wished for more detail in addressing unsustainable practices. Two-thirds of LEAF users found criteria to have just the right depth. Approximately one-sixth of LEAF users found LEAF criteria too detailed, and one-sixth found them to be not detailed enough.

2.2.6 Individual background of users. LEAF and MGL are both primarily designed for biology, life science and chemistry labs. While not limited to these, they are also being implemented in some engineering, material sciences, and clinical labs. In our survey, 62.5% of LEAF and 82.4% of My Green Lab® participants are classified as biologists, and 29.2% and 14.7% as chemists, respectively. The remaining participants have different backgrounds. LEAF has categories on teaching and research quality that are not represented in MGL. MGL includes topics on organismic biology, *i.e.*, for animal research and fieldwork, which LEAF fully lacks. The good fit to biology and chemistry labs is reflected in the survey participants' positive rating of the appropriateness of the programs. Even participants in other research fields rated the appropriateness as 'appropriate' ($\text{mean}_{\text{LEAF}} = 2.83$, $\text{mean}_{\text{MGL}} = 2.55$, scale 0–4, not at all to very appropriate for the specific research field). Nevertheless, chemists rated the appropriateness for their specific lab in LEAF +0.74 higher than MGL (Bootstrap-test, $p = 0.073$, $n_{\text{LEAF-chemistry}} = 7$, $n_{\text{MGL-chemistry}} = 5$). The rating difference between the two programs, as assessed by biologists, was negligible (+0.11, $p = 0.682$, $n_{\text{LEAF-biology}} = 15$, $n_{\text{MGL-biology}} = 27$, see Fig. 2g). We did not find any correlation between research background and rating on aspects of the programs, *c.f.* Table S1.† One MGL chemist stated that they wished for more advice on chemical wet labs. We see, *e.g.*, potential in both programs for more instructions on how to optimise solvent selection, awareness about the impact of solvents on climate change, and instructions on solvent recycling.

Additionally, we investigated if differences in ratings might occur according to staff type. Non-scientific staff (*i.e.*, technical assistants and administrative staff) rated both programs similarly. In the scientific staff group (PIs, PhD students, postdocs, other researchers), we saw differences between the programs in multiple aspects, some of them with a significantly higher rating of LEAF over My Green Lab® (significant if $p < 0.05$, compare Fig. S2a–e,† all Bootstrap-test, all $n \geq 14$ and scale 0–4, not at all to very good, if not stated differently): appropriateness for the specific lab ($\text{mean}_{\text{LEAF}} = 2.93$, $\text{mean}_{\text{MGL}} = 2.38$, $p = 0.035$), German framework suitability ($\text{mean}_{\text{LEAF}} = 3.07$, $\text{mean}_{\text{MGL}} = 2.13$, $p = 0.002$), overall program rating ($\text{mean}_{\text{LEAF}} = 3.21$, $\text{mean}_{\text{MGL}} = 2.72$, $p = 0.098$), greenwashing risk (scale 0–2, high risk to no risk, $\text{mean}_{\text{LEAF}} = 0.93$, $\text{mean}_{\text{MGL}} = 0.56$, $p = 0.09$), and resources ($\text{mean}_{\text{LEAF}} = 3.2$, $\text{mean}_{\text{MGL}} = 2.56$, $p = 0.037$, $n_{\text{LEAF}} = 8$, $n_{\text{MGL}} = 9$). From the comments section, we see that missing literature/publication references in MGL were only stated by scientific staff. Also, the missing adaptation to the German framework was mentioned in the free comments section mostly by scientific staff (5 times mentioned, of which 4 were scientific staff).

2.2.7 Suitability for German framework. While neither program was developed in Germany, we want to understand how well they fit national and local regulations. LEAF allows institution administrators to enter local guidance to criteria, making it adaptable to national or local frameworks. This is a very efficient way to implement solutions tailored to the local needs, rules and regulations by one person for a whole institution. My Green Lab® does not offer such tailored adaptation; instead, it has a few criteria that, while relevant in the USA, are obsolete in Germany as well as the rest of the EU, partly due to national and European regulations (*e.g.*, prohibition of water-vacuum aspirators, limited availability of take back schemes).

Even though MGL provides translations in German (and other languages), comprehensibility is sometimes limited by the quality of the translation. However, MGL has recently employed a German employee and aims to address this issue (personal conversation).

The above-mentioned circumstances are strongly mirrored in our survey: LEAF was rated to be significantly better adapted to the German framework than My Green Lab® (Fig. 2h, $\text{mean}_{\text{LEAF}} = 2.96$, $\text{mean}_{\text{MGL}} = 2.48$, Bootstrap-test, $p = 0.039$). 15.6% of My Green Lab® users expressed their wish for better adjustment to German/EU regulations in the survey's non-specific comments section.

2.2.8 Greenwashing risk. While any efforts taken by labs are currently fully voluntary, future demands of funders on scientists to take sustainability actions may lead to greenwashing attempts. Currently, only some funding agencies demand an evaluation of sustainable lab work.[12–17] To ensure the credibility of certificates, it is thus important to close potential loopholes of undeserved certification.

Franssen *et al.*, summarising LEAF benefits in the Netherlands, see a risk of future 'goal displacement' such that increasing sustainability may become less important than 'scoring high' in certification when it becomes required.[24] They reference to former 'assessment systems affecting money or reputation' that have changed researchers' behaviours (*e.g.* bibliometric measures)[45,46] towards a culture of scoring high rather than performing better. If labs want to greenwash, they can currently do so, as there is no external validation of the certifications, such as an external audit.

Whereas participants in both LEAF and My Green Lab® perceived on average a moderate risk of greenwashing (scale 0–2, high to no risk, $\text{mean}_{\text{LEAF}} = 1.0$, $\text{mean}_{\text{MGL}} = 0.9$), the distribution differs highly between participants of the different programs (Fig. 3). The majority of LEAF users sees a moderate risk and only small groups see no or a high risk. Contrarily, only 41% of MGL users see a moderate risk, but 35% see a high risk and 24% see no risk.

We see multiple reasons for answering 'high risk'. There is a low threshold to overstate green behaviours, particularly in a multiple-choice questionnaire (in MGL, *e.g.*, 'we keep sashes of fume hoods closed all the time' rather than 'mostly'). We see an advantage in the LEAF program, as cross-auditing by research groups within the institution is requested. In our opinion, this leads to more objective answering and to the critical discourse of the criteria. Another advantage of LEAF is that it rather asks for systems to be in place to ensure certain workflows and how they are achieved/maintained instead of asking if actions are performed in a certain way.

2.2.9 Certification mechanism. Certification levels are reached in different ways in the two programs. LEAF demands certification renewal annually and is more rigid, asking for fixed criteria for each level (*c.f.* Fig. 4 'fixed criteria'). It ensures that certain very important criteria will be addressed at a given stage of the process of becoming a sustainable lab but also asks criteria that have very little impact on the individual level (adjusting screen brightness, for example, is only truly effective if many employees adapt). MGL demands recertification every

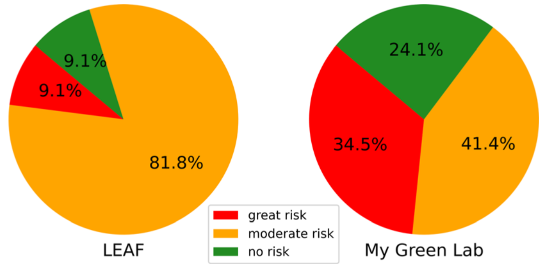

Fig. 3 Perceived greenwashing risk of the sustainability programs as rated by users of LEAF and My Green Lab®.

second year and awards certification according to the percentage of positive answers scored in the questionnaire (*c.f.* Fig. 4 'score'). We recognise the advantage of MGL's flexibility in acknowledging already achieved sustainability goals at any stage of the process. In contrast, LEAF does not recognise Gold criteria at the Bronze stage, for example. MGL emphasises the importance of keeping employees' motivation high by honouring achievements and positivity.

Nevertheless, there is a risk of bias in the way MGL performs scoring: there could be unbalanced progress with many less impactful measures possibly contributing to a high scoring level, even though really impactful measures have not been tackled. For example, we achieved 'Green' in MGL (highest level) but only 'Silver' in LEAF (medium) when implementing both programs in our lab (see detailed discussion in 'Impact of the programs'). To a broad audience, a 'Green' certification must create the image of a very sustainable lab, where one can expect to find the most impactful measures to be implemented.

We asked all survey participants what they thought of the possibility of compensating criteria of a level with other ones to still reach a given level of certification in comparison to having fixed criteria (Fig. 4). Multiple answers were possible. Only 24% of participants stated that compensation should be possible (as is the case in My Green Lab®, 'score'). 41% of participants desired fixed criteria (as is the case in LEAF). 48% of the participants indicated that compensation should be possible, but there should be a minimum of obligatory criteria that could not be compensated ('fixed criteria + score').

We have found that other certification standards, *e.g.*, the DGNB (German Sustainable Building Council,[47] Europe's largest network for sustainable building), use a system of variable measures and minimum requirements. They allow a certain flexibility to compensate for 'soft' criteria but ensure that the most impactful criteria will be implemented as they are set as minimum requirements at certain levels (compare Fig. 4).

2.2.10 Challenges and solutions. Besides challenges discussed above, users experienced and specifically mentioned in the comments section (for further detail, see Methods) a lack of financial and staff support to implement sustainability measures. 30% of survey participants affirmed that they would have liked staff support (*e.g.*, student/research assistant), and 9% mentioned the need for financial support, specifically for repairs and the purchase of more energy-efficient devices. As a solution and to justify support claims, we suggest users

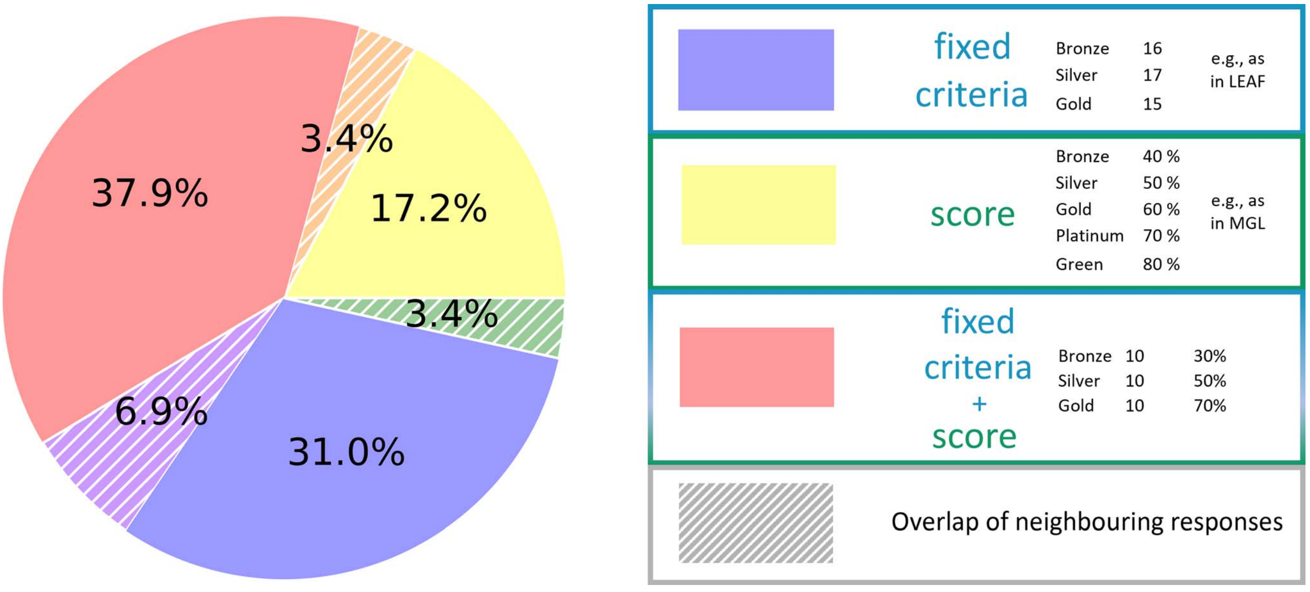

Fig. 4 Users' opinions on the best criteria demanded for reaching certification levels. Multiple answers were possible. Multiple answers chosen are depicted as hatched intersects in the respective colour mix.

inform the management of their institution about the potential of monetary savings linked to ventilation optimisation[40,48] and the return on investment of optimising device management (*e.g.*, freezer management, time switches for drying ovens, *etc.*).

For some users, either program lacks specificity for the particular research lab. MGL shows users only the relevant topics for their labs, but both programs miss some aspects. For research labs with dry lab/computational work, Green DiSC, an open access sustainability program for computing activities can be supportive.[49] Users criticised that MGL does not cover aspects of teaching. Not listed under a distinct teaching category, but in the Green Chemistry category, MGL together with Beyond Benign and Millipore Sigma have published a free 'Guide to Green Chemistry Experiments for Undergraduate Organic Chemistry Labs', *i.e.*, improving chemistry teaching.[50] Besides the sheer coverage of one aspect that everyday lab life is faced with, we see an enormous value in focusing on teaching sustainable practices in natural sciences: this is the implementation and amplification of best practices in the next generation of (wet lab) scientists. Thus, in both programs a stronger focus on teaching could lead to a long-term change and many of the criteria would become self-evident. Users stated that some criteria addressed estate questions that they could not address at the lab level, *i.e.*, that they felt were irrelevant. This is a misapprehension. Users should involve estates to jointly tackle, *e.g.*, ventilation optimisation, the most impactful measure. Furthermore, it was remarked that more research/publications on the topics (waste, energy, *etc.*) are needed.

9% of users claimed in the free comments section that exchange with other labs/peers was the most effective measure, or demanded more exchange between participating labs and a good network for exchange. Both LEAF and MGL encourage exchange, LEAF by their cross-auditing method, MGL with an exchange platform, the so-called 'ambassador program'. Challenges users experienced and specifically mentioned in the comments section were to involve and motivate unmotivated peers or stakeholders (11%). Challenges mentioned in both personal conversations and comments were that participants were overwhelmed with the number of measures and were unsure where to start, *i.e.*, how to prioritise, set responsibilities, and how to keep implementing changes regularly on a time scale of months.

Many of the above-mentioned challenges could be overcome with the help of commercial sustainability consultancies.[51–54] Clearly, the advantage of an expert audit leads to a highly tailored method and can overcome the mentioned shortcomings, but the dependency on a specialist may be a financially limiting factor. Thus, we suggest three add-ons from commercial consultancies to supplement the two major sustainability programs.

Firstly, doing an on-site inspection with the majority of lab members/stakeholders, potentially focusing in teams on categories (energy, water, *etc.*), helps tailor the generic measures to the individual lab and to engage everyone. Secondly, creating a project management plan, for example, with a prioritisation matrix,[51] including the feasibility of implementing a measure, impact on resource consumption, cost investment/return, impact on workflow, environmental benefits, and impact on employee motivation to prevent unbalanced progress or implementing only low-hanging fruits without addressing very impactful measures. Freese *et al.* have created an extensive open-access guidebook with measures ordered by their impact, which can be helpful in prioritising.[55] Thirdly, involving stakeholders, setting responsibilities, agreeing on due dates and regular meetings with an expert, ensures continuous improvement even after the first momentum of motivation has ceased.[51–54]

2.3 Decision-making guidance

When choosing a program, you should answer the following questions for your lab:

• Do you want to prioritise measures or do you prefer prioritisation by the program?

• What price are you willing to pay?

• Are there other labs in your institution that want to participate in a sustainability program that could do cross-peer-reviewing? If not, is there a sustainability manager at your institution who could perform the audit of your lab? Is there a person at your institution willing to take the admin role of LEAF?

• What is your research field?

• How important is the better fit to your national/local framework to you?

• How detailed do you want criteria to be (*e.g.*, detailed questions on specific devices (*e.g.*, glove boxes, incubators) or general ways on how to best operate groups of devices)?

• Do you want all or most lab members to be involved or just one or a few persons to be mainly responsible?

• Do you want to compare your lab rather to labs worldwide or within your institution?

• Are you interested in calculating your CO_2 savings?

LEAF has fixed criteria for each certification level, *i.e.*, prioritising measures, ensuring balanced progress across topics and the eventual implementation of the most impactful measures. MGL has variable criteria, thus allows for individual prioritisation and flexible recognition for any implemented measures, but risks leaving the most impactful measures unimplemented.

The user may see a strong argument in pricing, which is also influenced by the number of labs willing to participate at the institution. LEAF is priced per institution (£1100–2600, size dependent), MGL per lab (500–350 US$, dependent on the number of labs per institution). If more labs participate, LEAF is financially advantageous, and it fosters knowledge exchange between labs. However, it needs someone to coordinate the program within the institution. If there are few to no other labs willing to participate, My Green Lab® is advantageous because it is independent of present institution-internal structures, and pricing is per lab. Having more labs of an institution joining is always a good idea. Besides the positive effect on pricing, exchange between labs was one of the most useful and effective aspects stated by users of both programs. There is an implicit advantage in LEAF asking for an exchange with other labs by default.

The programs are differently suited for different research fields and the amount of teaching. MGL includes topics on organismic biology, *i.e.*, for animal research and fieldwork, which LEAF fully lacks, but the latter program includes teaching and research quality. Even though we saw the trend that chemists rated LEAF higher in the overall feedback and found it more appropriate for their specific lab, we could not find a significant difference between the programs' ratings (Fig. 2b and g). Independent of the research field, LEAF was rated significantly better adapted to German/EU regulations (Fig. 2h). MGL was rated significantly better in the ratio of time-to-fill-out *vs.* benefit (Fig. 2f).

Choosing between the systems can be eased by deciding on the preference of rather broad, general but prioritised criteria (LEAF) or very extensive, very detailed, and device-specific criteria (My Green Lab®). Moreover, LEAF aims to keep the effort for most staff low, involving a minimum of one or two responsible persons to delegate or organise all change. However, to address the high turnover-rates of staff in academic research labs, it requires annual auditing. MGL argues on educating people with the assessments and driving cultural change when reaching a critical mass of employees being engaged. Thus, at least 50% of lab members have to fill out the questionnaire. However, MGL demands recertification only every second year. This might lead to a situation where the percentage of lab members that have participated in MGL has already dropped significantly after the first year of running MGL in the lab.

If you are interested in comparability worldwide, My Green Lab® is represented in 46 countries, LEAF only in 15.[27,30] As LEAF is priced and run institution-wise, it has a stronger distribution within one institution and offers more comparability locally. If you are interested in calculating approximate CO_2 savings, LEAF offers this option.

Generally, when considering executing one of the programs in the lab, one can be assured that they are both very helpful in making labs more sustainable and improving employees' motivation to work sustainably. Nevertheless, if programs are executed somewhat negligently, there are ways around addressing the most impactful measures and still achieving high certification. After some motivation-boosters and low-hanging fruits, the most impactful measures must be tackled, *i.e.*, ventilation (even if estates say it is not possible) and purchase optimisation.[36]

3 Conclusion

This publication's intention is not to evaluate a better program but the program that is best suited for individual needs. Any implementation of sustainable measures in laboratories makes science greener. Succeeding an exhaustive literature review on the saving potential of the proposed measures by the programs, we could show that they both have a great potential to significantly reduce science's carbon footprint and even enhance research quality. After a thorough comparison of user experience, we conclude that both programs are powerful tools for increasing lab sustainability. They significantly enhance users' motivation to work sustainably and, therefore, have even more impact in the long term. We elucidated specific advantages and weaknesses for individual backgrounds, wherefore we provide users with specific decision-making guidance. We see a key difference between the programs in the fact that LEAF has fixed criteria for each certification level, ensuring balanced progress across topics and that the most impactful measures are addressed at the latest in Gold certification. Due to the fully flexible criteria of MGL, it is possible to reach the highest level in MGL without addressing the most impactful measures but many low-impact measures. Still, the motivated user will find the necessary information on the impact of measures within MGL and can target the most impactful criteria.

Both programs offer room for improvement in terms of addressing users' needs and becoming greenwashing-proof. Nevertheless, one needs to keep in mind that the programs are low-threshold, bottom-up initiatives to improve the sustainability of lab work and are not firm certification tools based, *e.g.*, on ISO/EU/EMAS norms. The programs grow and develop continuously and strongly support the green labs movement. However, in times of open access, programs with user fees, *i.e.*, both LEAF, being university-bound, and MGL as a non-profit organisation, are exclusively available for those holding the financial means. To widely enable growing best practices in sustainable lab work, we urge for the existing programs to become open-access or for a new open-access program/tool to become available to share the common knowledge on sustainable lab work.

In addition to the bottom-up strategies, the research community needs top-down guidance: clear regulations from funding agencies demanding certain minimum criteria. We embrace European funding agencies' efforts to join forces for a holistic European strategy.[56] These joint forces could potentially provide the financial means for an open-access solution. Moreover, research groups and institutions need financial and staff support to optimise sustainable processes. To avoid greenwashing, external validation and proof of implementation of the most important sustainability measures are needed in the long run.

4 Methods

4.1 Survey questions & answers

We designed a Germany-wide study available in English and German on LimeSurvey. Full survey, results and all analysing code can be found in Zenodo repository.[44]

4.2 Acquisition of survey participants & sample composition

The survey was run from September 2023 to February 2024. It was sent out to the administrators of all academic institutions that run LEAF in Germany and to My Green Lab® to distribute it to My Green Lab® points of contact in participating labs. Both were asked to forward it to lab users. We received feedback from 5 of 6 institutions participating in LEAF and from 11 of 14 institutions participating in My Green Lab®. In total, we received feedback from 24 LEAF and 35 My Green Lab® users. LEAF participants indicated an average interest in sustainability of 3.3, My Green Lab® participants of 3.5 (corresponds to high to very high, scale 0–4, not at all to very high interest). Asked was 'How high is your interest in sustainability in your private everyday life?'. 62.5% of LEAF and 54.3% of My Green Lab® participants are scientific staff, 37.5% and 40% are non-scientific staff, respectively, 5.7% of MGL participants could not be assigned to scientific or non-scientific-staff. 62.5% of LEAF and 82.4% of My Green Lab® participants are classified as biologists, and 29.2% and 14.7% as chemists, respectively. The remaining participants have different backgrounds.

4.3 Data preparation

Classification of participants as 'biologist', 'chemist' or 'other' was performed using clusters of chemistry/biology-related terms (for details, see Dataset & Analysis in the Zenodo repository).[44] Technical assistants and administrative positions were grouped as non-scientific staff. PIs, PhD students, and researchers were grouped as scientific staff.

4.4 Statistical analysis

The study consists of two surveys: a shorter survey for participants before certification by the respective program and a more extensive one for participants after certification by the respective program. Questions that could only be adequately answered after some experience with the program were only shown in the more extensive survey to participants who had worked with the program for at least one certification round. Data was pooled using the Stata do-file (Zenodo repository). Ratings of program aspects were examined with Bootstrap-test[57] in Python to calculate significance levels. The significance of the paired dependent variable 'Motivation increase' (motivation to work sustainably before and after program intervention) was analysed using a non-parametric Wilcoxon signed-rank test (Zenodo repository).[44]

4.5 Plots

We chose violin plots for all samples $n \geq 10$, *i.e.*, comparison between the programs without further subcategories. Violin plots show the entire distribution of data, including tails and outliers, which bar plots fail to describe. We consider it important to show a few users' little satisfaction with certain aspects of the programs, rather than showing a mean value that neglects extremes. For $n < 10$, *i.e.*, comparison between the programs and research background/staff type, we consider a visual bias to be too strong. $n < 10$ can only tell trends, not reliable distributions, thus we focus on the mean, *i.e.*, bar plots, but still show the distribution as dots.

4.6 Grouped evaluation of questions

The topics 'Quality of Resources', 'Structural Aspects of Program', and 'Improvements outside Sustainability' are the mean values of various questions (see Table 2). For each user, the average of the subquestions was calculated to obtain the value of the respective column title.

4.7 Comments section

In order to acknowledge the importance of answers in the free comments section, the paragraphs above discuss them in detail, even if mentioned by a single participant.

4.8 Comparison of the programs in the Bruns Lab

The LEAF program was implemented in the Bruns Lab already in 2019 at the University of Strathclyde. Current lab members at TU Darmstadt were not involved back then. The research group moved to TU Darmstadt at the beginning of 2022. We started re-implementing LEAF in the Bruns Lab in November 2022, and the My Green Lab® program started in January 2023. During implementation, the lab comprised nine lab members, of which seven were actively working in the lab. Lab space comprises three chemistry, one analytical, and two biosafety level 1 lab rooms as well as a chemical storage room, resulting in 196 m^2 in chemistry, 41 m^2 in the analytical lab, and 88 m^2 in the biological labs.

Data availability

The data that supports the findings of this study, including survey questions, survey results, data preparation, and analysis, are available in Zenodo at **https://doi.org/10.5281/zenodo.12722163**.

Author contributions

Bianca Schell: conceptualization; methodology; formal analysis; investigation; data curation; writing – original draft; writing – review and editing; visualization; funding acquisition. Nico Bruns: conceptualization; resources; writing – review and editing; supervision; project administration; funding acquisition.

Conflicts of interest

The authors declare no conflict of interest.

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