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Sustainable science or business as usual? Exploring awareness and actions in German University Laboratories

Caterina Baars, Patrycja Karwasiecka *, João Henrique Paulino Pires Eustachio, Andrea Dobri, Jelena Barbir, Sven Kannenberg, Walter Leal Filho

Hamburg University of Applied Sciences, Faculty of Life Sciences, Research and Transfer Centre Sustainability & Climate Change Management (FTZ-NK), Ulmenliet 20 / 21033 Hamburg, Germany

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A B S T R A C T

As sustainability research covers many disciplines, it is important to understand how sustainable research itself is. Previous studies have shown that laboratories, a core infrastructure of research, consume a large number of resources. However, overall understanding and identification of actions that can improve the current situation is rather unclear due to a large data gap on the opinions and attitudes of staff and students within institutions. This study explored sustainable actions among laboratory staff and students in a sample of German universities, in the categories of materials, devices, procurement, waste disposal, and awareness. For this purpose, a mixed-method approach was applied, consisting of a quantitative survey answered by 81 laboratories, and a qualitative interview conducted within 9 different universities. One of the key findings is that the inclusion of more sustainable laboratory activities (e.g. efficient waste and equipment management) was mostly undertaken by the laboratory staff themselves, which led to many bottom-up approaches. However, the necessary framework from the administration and institutional support is often missing or is rather limited, which hinders progress in existing initiatives and to take advantage of their great potential. To achieve effective change, it is essential to engage all stakeholders in the institution, laboratory personnel, and institutional administrators. The findings provide valuable insights into the landscape of German university laboratories and their actions and highlight potential areas for structural intervention to make the laboratory operations in universities more sustainable.

1. Introduction

In the face of the climate crisis, and the finality of planet Earth's resources, it is undeniable that we need to find alternatives for the business-as-usual scenarios, to ensure a liveable future for all [14]. This search for said alternatives includes examining the resource-intensive areas, and one of these areas lies right in the heart of academia and science: laboratories [9]. The research on this topic shows that the consumption of energy and resources in laboratories is high [25]. On average, a single laboratory building consumes three to five times more energy and water than an office building [1]. The individual CO_2 emissions of scientists from research institutes range between around four and 18 tons per year, with the latter figure being 1.6 tons higher than the average total emissions of German citizens. The sources of these emissions are diverse. Above all, air travel and electricity consumption in laboratories are responsible for a large proportion of the greenhouse gas emissions generated [2]. Many large pieces of equipment are operated continuously, contributing to the high consumption of resources and to the great CO_2 footprint of laboratories. In addition, the continuously increasing plastic consumption in laboratories is of central importance given the waste problem [12]. Urbina et al. [25] estimated that roughly one research department accounted for plastic waste of a rough estimate of 5.7 million 2-litre plastic bottles.

Laboratories in Germany must adhere to strict safety regulations, including the Hazardous Substances Regulation (Gefahrstoffverordnung), and regular training sessions and safety drills are important for fostering a culture of safety awareness among staff and students. Also, awareness of ethical standards in research is widely present. This includes understanding the importance of transparency, data integrity, and responsible conduct in research. But this does not necessarily

* Corresponding author.
E-mail addresses: baarscaterina@gmail.com (C. Baars), patrycja.karwasiecka@haw-hamburg.de (P. Karwasiecka), joao.eustachio@haw-hamburg.de (J.H.P.P. Eustachio), andrea.dobri@haw-hamburg.de (A. Dobri), jelena.barbir@haw-hamburg.de (J. Barbir), sven.kannenberg@haw-hamburg.de (S. Kannenberg), walter.leal2@haw-hamburg.de (W. Leal Filho).

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translate into a sustainable science culture. Looking at the laboratories in German Higher Education Institutions (HEIs), the institution itself plays a crucial role in sustainable development, producing and sharing knowledge, as well as educating students for their future careers and cultivating their perception of sustainability [15]. HEIs around the world are increasingly adding the topic of sustainability into their agenda, partially motivated by upcoming policy regulations. With the German federal system, the efforts regarding sustainability within the HEIs are very heterogeneous, depending on the respective state and its policies. Throughout Germany, there are a few HEIs that are even committed to becoming carbon neutral on top of sustainability reporting, but this remains a rare case [16]. A great number of institutions have not applied sustainable strategies to their institutions, leaving a gap for a holistic institutional approach and top-down measurements that steer the existing grass-root actions in a direction. Concludingly, these missing sustainable actions might also apply to the laboratory area.

The situation described above and the fact that a great majority of HEIs in Germany operate science laboratories that have a significant impact on the environment suggest that there is an urgent need for action to change current trends. So, as Sustainability Research enters a lot of disciplines, the question is how sustainable is research itself in HEIs, and how to improve. However, the data about sustainability in laboratories in general but also for Germany is very scarce, leaving a great data gap that is essential in order to build recommendations that are adequate to the needs.

Given the need for insights into the current situation, the following research utilizes a mixed-methods approach to analyze the current situation in German university laboratories, both on a quantitative and qualitative facet. Results are then described and compared to existing literature. The main objectives of the research were:

a) to assess the status quo of sustainability within German university laboratories in key areas such as material, reagents, waste disposal, devices, and sustainability awareness
b) to build recommendations based on the findings to improve the sustainability practices within the university laboratories

While sustainability is a complex, multifaceted concept encompassing the three interconnected pillars of economic, environmental, and social dimensions (see Fig. 1), this research intentionally narrows its scope to examine environmental aspects in depth, in addition to assessing the awareness of the sustainability concept in the laboratory environment.

Nevertheless, although the study centers on environmental considerations, these cannot be fully disentangled from economic and social dimensions. Consequently, references to these additional pillars will appear throughout the study, but with less emphasis. Funded on the results, theoretical and practical recommendations are given in the end to support the universities in their way to a more sustainable science and

Fig. 1. Sustainability Dimensions in the area of laboratories, modified by the authors, original: Dr. Kerstin Hermuth-Kleinschmidt.

laboratory operation.

2. Methods

A mixed-methods approach was used to determine the status quo at German university laboratories on the topic of sustainability. First, quantitative data was collected utilizing a nationwide survey in the LimeSurvey software (LimeSurvey Cloud Version 6.6.3). The survey was built corresponding to key areas identified with literature research, resulting in the key areas of material and reagents usage, procurement, waste management and disposal, and awareness (see Supplementary Material: Sustainability in the laboratory – Survey).

A total of 81 respondents took part in the survey. The data was then analyzed using SPSS (version 28) with the help of descriptive statistics.

In addition, online group and single interviews were used to provide more detailed insights into the higher education landscape. The interviews were conducted with 20 test subjects recruited by a snowballing system within the institution. The majority of these were laboratory managers, employees, and researchers. Various aspects were covered in the interviews.

The interview and survey included similar questions, such as characteristics of the laboratory (the department, the equipment, the user structure), the availability and consumption of materials, reagents, and equipment. The focus here was on the handling of solvents, hazardous substances, and repair and reuse options. Other topics included the procurement process, in particular responsibilities, the integration of sustainability and transparency, as well as waste management, with a focus on recycling and sharing models. The items were then introduced into a coding system, and analyzed with MaxQDA (Version 24), which resulted in the final code tree that categorized the key answers according to the research objectives (see Fig. 2).

2.1. Sample description

The sample in the quantitative section comprises around 81 respondents from German university laboratories, 51 % of whom identify as male, 43 % as female, and 6 % as diverse. The respondents' highest educational qualification was a Master's degree (40 %), doctorate (17 %), (specialized) high-school diploma (14 %) and Bachelor's degree (11 %). The majority are located in a public institution (91 %), only a minority in private institutions (9 %). When asked about their primary role at the institute, around a third categorised themselves as employees (33 %), a third as researchers (32 %), and a further third as students (14 %), teachers (5 %), and several of these categories (16 %). Looking at the subject areas, chemistry (53 %) and biology (17 %) are predominantly represented, with the remaining people split between the categories 'other', physics, or medicine (cumulative 30 %) (see Fig. 3).

The sample in the qualitative section included 20 individuals, all from public universities within Germany. The interviewees ranged from employees, researchers, and teachers, stemming from around 14 different working groups and laboratories, primarily in the biotechnological and organic chemistry area.

3. Results

3.1. Material and reagents consumption

A wide range of materials can be used to conduct research, and while some are specific to the research discipline, other disposable materials cross disciplinary boundaries, such as disposable gloves or foil. As part of the analysis, the respondents were therefore asked to self-assess their use of these materials (see Fig. 4).

Observing the estimated consumption of consumables, it can be seen that a few selected materials have a high consumption regardless of the department. The six items with the highest estimated consumption, based on cumulative percentages of the two highest consumption

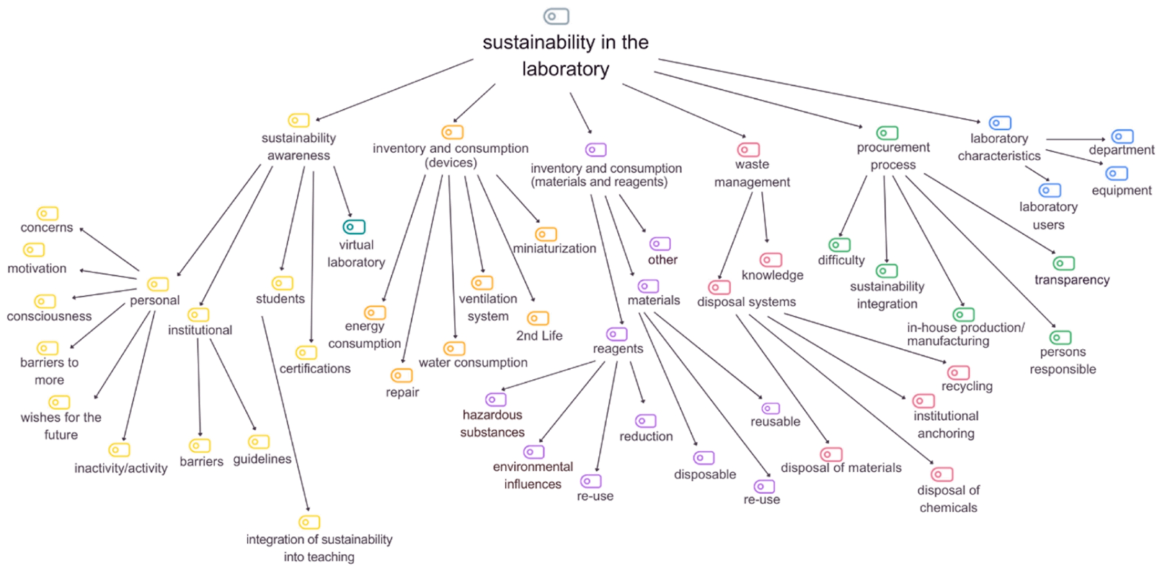

Fig. 2. Final coding scheme for the interviews.

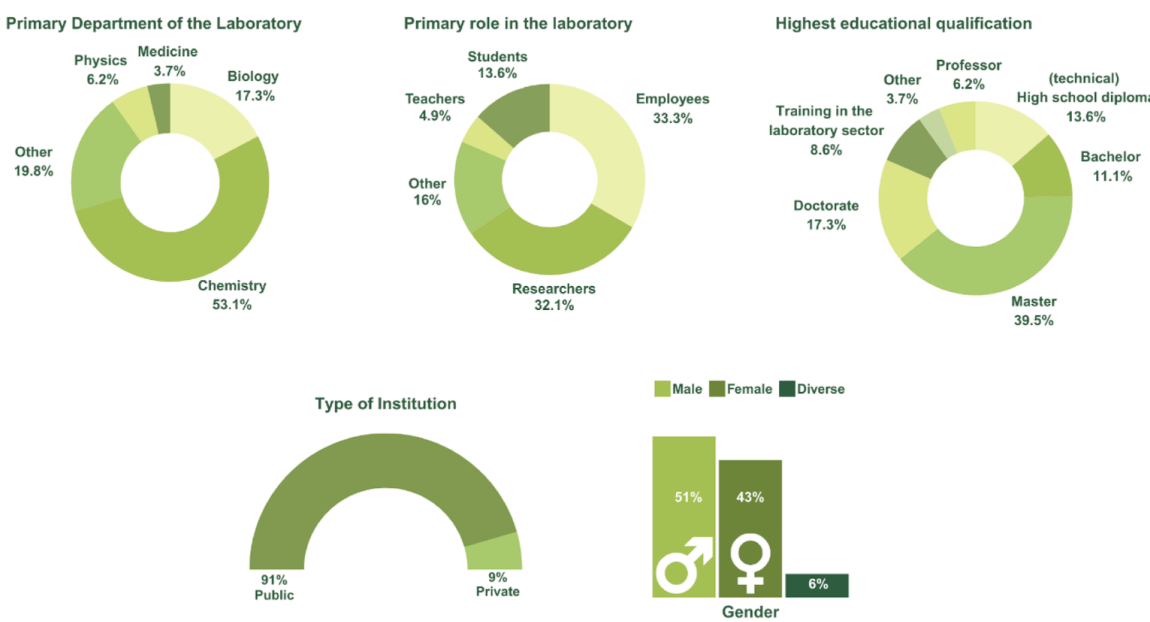

Fig. 3. Sample description of the quantitative analysis.

categories 4 and 5, include disposable gloves (65 %), disposable containers (53 %), multichannel pipette reservoirs (27 %), weighing dishes (26 %), and filter paper (25 %). Material consumption also varies by department, a closer look into the splitted data can be found in appendix A.

However, some materials that are intended for single-use do get used multiple times, with more than a third of the respondents following that practice,e.g. with the following items: disposable syringes, pasteur pipettes, t cell culture vessels. Examples of reuse by washing and rinsing of syringes and plastic lids were given in the interviews (see appendix B).

The reagents used depend heavily on the research focus of the laboratory. In particular, reagents classified as hazardous substances pose a significant risk to human health and the environment if handled and disposed of improperly. Around 45 % of the test subjects stated that they use hazardous substances because no alternative is possible, 24 % because handling is part of the teaching program, and 20 % because no alternative is known. The interviews also showed that the handling of hazardous substances teaches students to a certain extent how to deal with them:

*“**Some things can’t be replaced** because then you can’t do the whole experiment.” (03)*

*“But I […] don’t think that’s the case at all. **Why do you have to put something toxic in the student’s hand just so that they have worked with it once and know that you can use it?** […] To be honest, I don’t think that’s very good. But again, that’s your own opinion.” (02)*

A complete avoidance of hazardous substances is not yet conceivable in the field of research and is also rather unrealistic in everyday student life. It is therefore of the utmost importance to take appropriate safety measures and strictly adhere to the regulations for the safe handling of these substances. When hazardous substances are used, a majority (81 %) stated that they are used under increased safety conditions, around 57 % use substitutes where possible and half rely on reduced quantities:

*“So we have two experiments in organic chemistry, […] where **we use or produce more substances that are really harmful to health** […]. And*

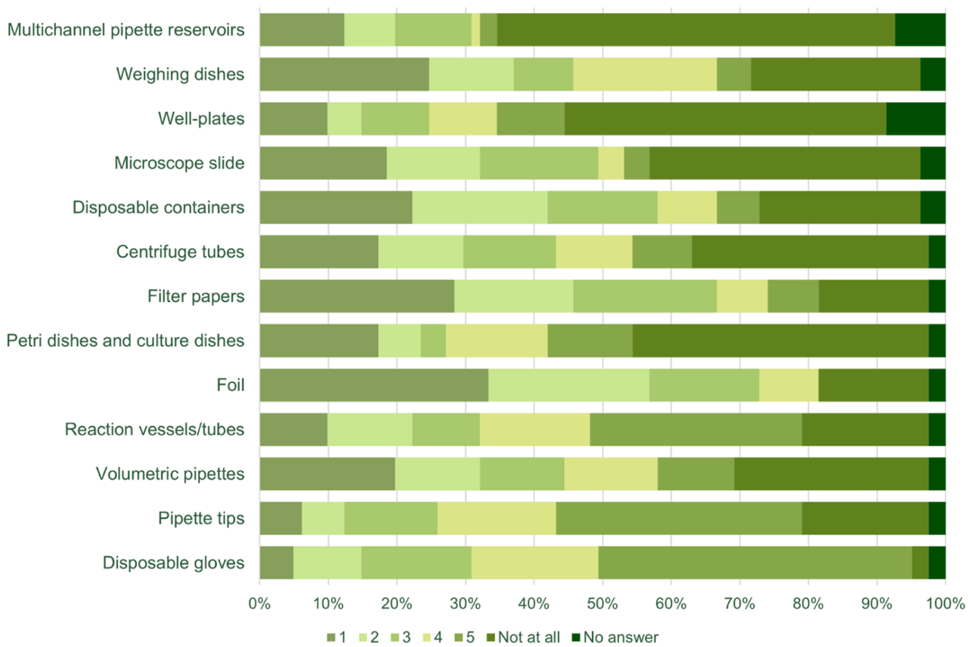

Fig. 4. Single-use material consumption, on a 5-point-likert-scale, with 1 being the lowest indicated usage and 5 being the highest.

that's always the problem, of course. ***We are looking to see if we can replace it."*** *(03)*

"Otherwise, yes, you can't really replace much else in cell culture. FPS is difficult, costs money, ***cell culture is very expensive and if you then want to switch to alternative, synthetic alternatives, it's twice, three times, four times as expensive,*** *which makes it extremely difficult.* ***Don't change your running system is sometimes the motto here in the lab. Sounds bad now, but we try our best.*** *You can always look at new protocols, but it's difficult with tried and tested ones." (04)*

When asked about a change in resource consumption, almost half (49 %) of the respondents stated that it had remained the same, for around a third (29 %) it had risen slightly, and for a minority (19 %) it had fallen slightly. The subjects who reported a change in resource consumption primarily cited a change in experiments (53 %) and a change in the number of students/staff (39 %) as reasons. In the context of resource consumption, it was also of interest to find out how many of the test subjects had already monitored their consumption and recorded the corresponding data. The results show that less than a quarter of the respondents collect data on their resource consumption (23 %). This quarter collected data primarily in the area of electricity (79 %) - the aspects of water, reagents, and disposable materials tended to be collected rather rarely (36 %).

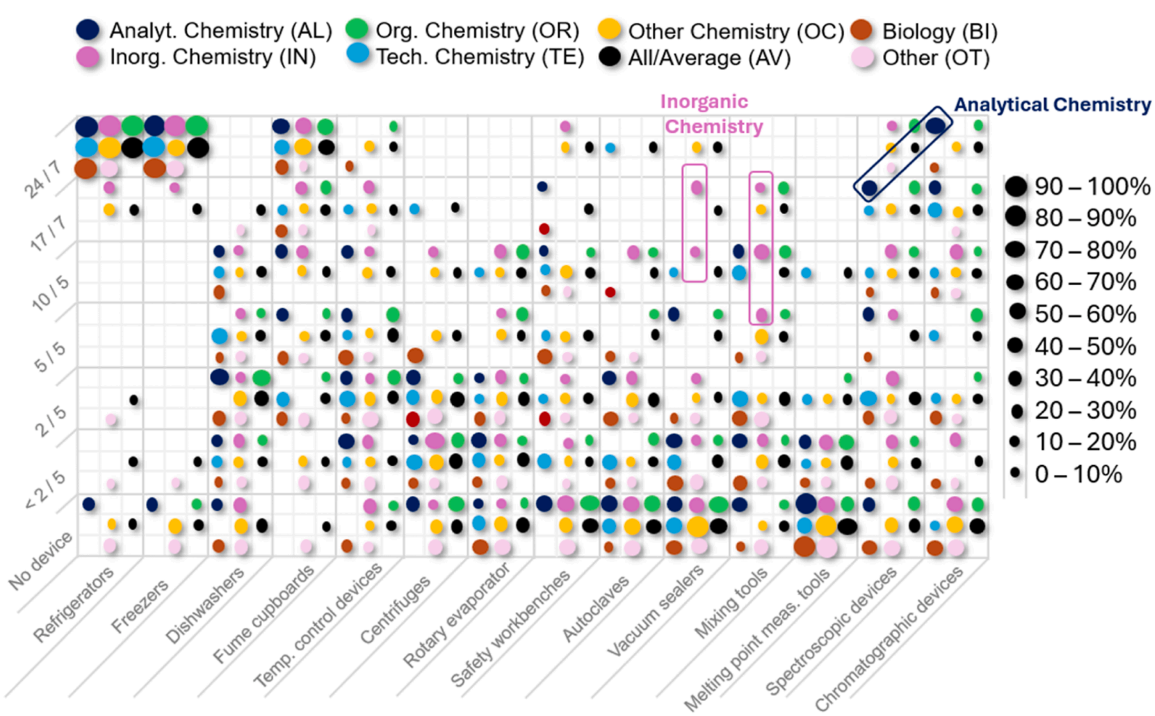

Fig. 5. Use of different laboratory equipment on average and by profession. The size of dots in each category represents the overall share (from 24/7 down to no use at all).

3.2. Devices and energy consumption

As shown in Fig 5, the study focused on 14 different types of laboratory equipment to determine the average use of equipment between different disciplines. Focussing on bigger sized equipment, the results show that chemistry related users (about 60 % of the surveyed) use refrigerators nearly to 24/7 (80 % AL, 89 % IN, 100 % OR, 100 % TE, 88 % OC) with the remaining percentage either on 17/7 usage (11 % IN, 6 % OC) or not having a respective device (20 % AL, 6 % OC). With freezers the picture is basically the same (80 % AL, 89 % IN, 90 % OR, 100 % TE, 69 % OC) with the remaining percentages on 17/7 usage (11 % IN) or not having a respective device (20 % IN, 10 % OR, 31 % OC). Laboratory dishwashers are used <120 h per week (<17/7) among the chemically related users with usage starting at 50 h (20 % AL, 13 % IN, 17 % TE, 7 % OC) and peeking at 10 h (40 % AL, 13 % IN, 73 % OR, 67 % TE, 33 % OC). Not having a respective device is also possible (20 % AL, 38 % IN, 33 % OC). Fume cupboards are mostly used 24/7 among chemistry-related users (60 % AL, 56 % IN, 55 % OR, 50 % TE, 63 % OC) and all chemistry or biology-related users confirm to have fume cupboards. Safety workbenches were not part of most laboratories (60 % AL, 67 % IN, 80 % OR, 36 % OC) with only technical chemistry (TE) having one in each surveyed laboratory, similar to the biology subgroup. Autoclaves for sterilization are in a similar situation (60 % AL, 50 % IN, 56 % OR, 33 % TE, 60 % OC). Spectroscopic and chromatographic devices are often used in Analytical Chemistry (AL) with 50 % in 17/7 for spectroscopic and 75 % in 24/7 for chromatographic devices.

3.3. Waste disposal

Concerning waste management, around 28 % of respondents state that they do not know how much effort their institutions make in recycling structures. A minority of respondents (5.6 %) reported a very high level of activity, while 15 % reported a high level. In contrast, around 18 % make no effort at all in this area, and around a fifth (22.2 %) report a low level of activity. Around 10 % perceive moderate efforts on the part of their institution.

The interviews show that the disposal of waste is often carried out by external waste disposal companies. This is done in accordance with the specifications of the respective disposal companies and following waste lists and codes. The proper separation of contaminated waste and chemicals as well as the separate disposal of chemicals from one another is particularly important. Many groups also endeavour to separate residual waste, plastic, and paper (see appendix B).

However, there are some challenges: Different laboratory waste follows separate disposal practices, with remaining gaps in between. For example, plastic and glassware that is (potentially) contaminated must be disposed of in the residual waste (further examples in appendix B):

"Glass waste is just as much of a problem. *This is high-melting glass, which is also not suitable for going into the glass container, where you might make new bottles out of it, because it simply can't be melted in that area. And that's why it ends up in the residual waste." (03)*

To counteract the high volume of waste, there are already approaches to enable reuse, e.g. by collecting used products such as pipette tips and glass bottles and sending the collection back to the producer for reprocessing (further examples see appendix B):

''But what we have established here at the centre is that everyone who uses [enterprise] pipette tips ***collects some of them centrally and sends them back centrally.*** *'' (04)*

3.4. Procurement

The procurement of new materials, reagents, and other items is an ongoing process for laboratories, which ensures that all necessary products are available for carrying out experiments. Regarding this topic, the extent to which the participating laboratories endeavour to integrate sustainability aspects into their procurement was investigated at various levels. The first question related to the consideration of energy consumption when purchasing new appliances. Over half of the respondents (55 %) stated that they were not involved in the procurement process. Around a fifth (21 %) take energy consumption into account, while around 16 % state that they do not. Just under 8 % do not know whether sustainability is considered in the procurement process.

The survey also included content on the extent to which collective ordering/procurement efforts are made at an institutional level. Around a third (32 %) of the respondents state that such efforts are made to a high degree, while 8 % say they are made to a very high degree.

Moderate efforts are reported by 8 % of respondents. In contrast, 22 % of respondents stated that no efforts were being made at all. A small proportion (11 %) states that a low level of effort is being made in this regard and around 20 % do not know to what extent their institution is making efforts in this area (see Fig. 6).

Overall, laboratories often place their orders in large quantities. The responsibility lies either with the laboratories themselves or with a central organisation that procures the required materials and reagents. It is becoming apparent that the budget plays a central role in procurement. Those responsible are often guided by the product prices, which can be to the detriment of sustainability:

"[Company name] recently sent us information that they produce their plastic items using sustainable raw materials. ***We could buy them, but of course, we only have a limited budget*** *and we always have to be careful if it becomes too expensive and we might not be able to buy other things as a result.'' (03)*

''[…] for the majority of products, ***it's still the price that counts.*** *[…] whatever is the cheapest and is produced a lot by the supplier, that's what people buy.'' (04)*

Another frequently discussed challenge is the transparency of the self-claimed sustainability. Understanding the information given on websites and product information is time consuming, which is why this aspect sometimes has to be neglected:

"You have to look at each product individually, check and search. ***We don't have the time****, which is why I honestly admit that* ***we don't do it enough*** *and I would expect the purchasing department to look for and recommend alternatives, but unfortunately,* ***we don't have the capacity****." (04)*

"What I have seen with sustainable or more sustainable products is that they are ***often a bit more expensive*** *and sometimes, […] it is usually* ***not clearly stated what the benefit of the product is.*** *It just says this and that is included and that's it.* ***So there's usually no description of the product included.*** *'' (01)*

"I find it ***very difficult to understand*** *on the company websites what exactly is sustainable about the product.'' (04)*

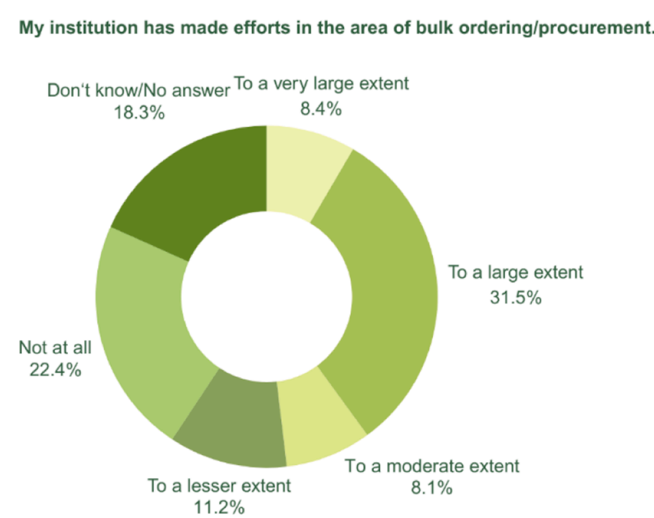

Fig. 6. Institutional efforts in bulk ordering.

3.5. Awareness

In order to examine and analyse sustainability awareness in the individual institutions and among the test subjects, the concept was considered at an individual and institutional level and the challenges and potentials were also examined. Looking at institutional awareness and existing measures, the most frequently mentioned points were raising staff awareness (18 %), the energy consumption of laboratory equipment (18 %), reuse of laboratory materials (15 %), and recycling structures (15 %). These factors are also found to a moderate extent in the minimisation of single-use plastics (24 %), water conservation (19 %), and the reuse of reagents (15 %). For most endeavors, however, the proportion of respondents stating 'to a small extent' or 'not at all' predominates (see Fig. 7).

At the individual level, there was already a strong awareness among the respondents. The majority of respondents (81 %) are aware of the environmental impact of laboratories, with around 48 % even stating that they are fully aware of this, while an even larger majority (89 %) are in favor of the relevance of sustainability, with around 60 % even considering it to be very important. In contrast, however, only 66 % have already dealt with sustainability in laboratory operations, 41 % of them to the full extent. The statement 'I have already tried to make my work more sustainable' was agreed to by 24 %, 43 % to the full extent. This cumulative majority accordingly provided some examples of actions that have already been realised:

*"**Started a media bottle collection**, where PAN takes back bottles with culture media. Ten labs participate in this initiative, which is highlighted on the sustainability homepage of the university clinic. **Engaged with the sustainability manager and participated in internal sustainability groups (procurement, clinic), contributing to the first sustainability report**, and attending networking meetings."*

*"**I initiated a project to ensure our sterile workbenches are turned off in the evening**, and talked to colleagues about sustainable lab management, which may have contributed to several of our **ULT freezers being adjusted to −70 °C**. We also started using **LEAF** and began **collecting clean hard plastics** for recycling."*

*„**Turn off fume hoods when not in use** for extended periods. **Consolidating drying ovens** with another lab. "*

*"**Experimentally evaluating alternative concepts** for handling backups, which could reduce plastic waste by up to 30 % compared to standard protocols."*

*"Adding **stickers to paper towel dispensers**, asking users to limit themselves to 1–2 towels. Switching to **Blue Angel-certified office and hygiene products**."*

*„I had a **My Green Lab certificate** in my previous lab (during my PhD), now I have to start over again (PostDoc)"*

*"**Freezer temperature adjusted**, using glass instead of plastic when possible, **separating waste, recycling plastic and styrofoam.**"*

*"**Reducing air exchange from 8x to 2x**, collecting empty pipette tip boxes for pickup by the manufacturer (Biozym), who forwards them to a regional supplier for granulate production used in window manufacturing."*

*„In teaching, **remind students that with good planning, they can save materials** quickly and efficiently"*

*"**Reusing** pipette tips, **turning off PCs and equipment** after use, **minimizing solvent consumption in HPLC.**"*

*"**Cotton lab coats** for visitors instead of disposable ones."*

The majority of respondents (89 %) would be willing to make their work in the laboratory more sustainable, with around 58 % strongly in favor of this.

Another question in the area of sustainability awareness was which factor the participants perceived as the greatest challenge in their organisation. Above all, the lack of human resources was perceived as the greatest challenge by the majority of almost all groups, except students. This was followed by a lack of financial resources, a lack of infrastructure and a lack of monitoring systems. This assessment was also reflected in the interviews (see appendix B).

The interviews also highlight a desire for clear guidance from the upper management, preferably connected with specific information on practicability (further examples see appendix B).

*"[…] I think the one or other **suggestion in the management function** would certainly also be very desirable." (06)*

*"In fact, with most of the things we use, **I wouldn't know where I could order more sustainably**, […]" (05)*

The lack of motivation on the part of the lecturers was perceived primarily by the students, while the lack of motivation on the part of the students received a low percentage of approval.

Finally, respondents were asked about their assessment of the sustainability potential of various measures. While a large majority of students (55 %) and researchers (60 %) would primarily like to see information on sustainability, around a third to a quarter of teachers, employees and other respondents said the same. The situation is different when it comes to more resources, motivational incentives, and regulations/guidelines. Here, the majority in almost all groups are in favor of great potential for more sustainable laboratory operations. Another aspect that was frequently mentioned was the building services and technology:

*"Honestly, the **greatest opportunity**, but also the **greatest difficulty**, is the building services" (05)*

*"Why does a ventilation system have to run if nobody is working in a laboratory? **Completely superfluous**. It's just that the technology simply doesn't allow it." (05)*

The participants were also asked whether they collect data on their

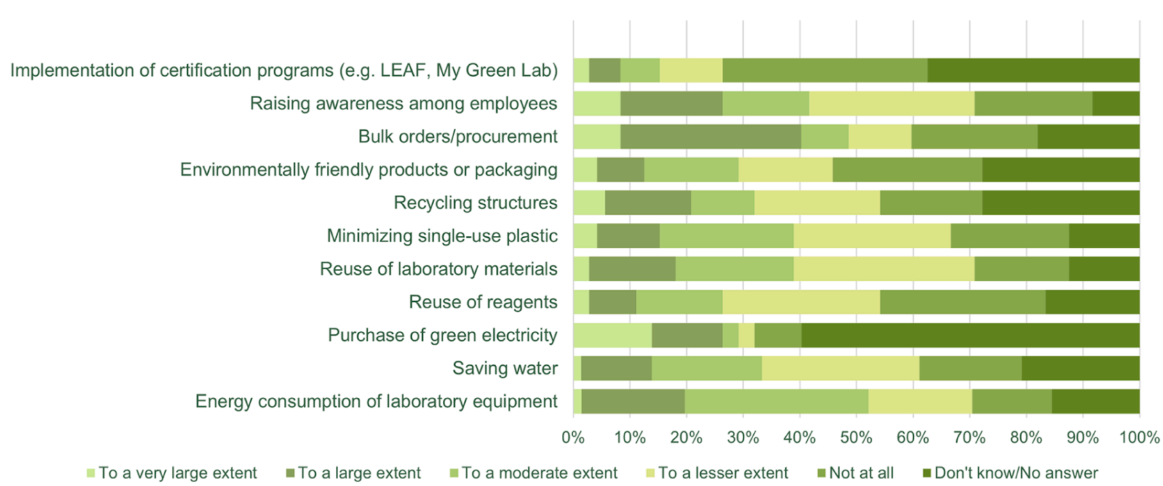

Fig. 7. Institutional Efforts in various areas, sorted by a 5-point-likert scale.

resource consumption, to which only a minority of around 23 % answered ‘yes’. Of this minority, by far the most data on electricity consumption was collected, meaning that only a small number of people actually have data available on their resource consumption and neglect other resources such as water, reagents or similar.

4. Discussion

All responders showed a high awareness of the sustainability issue, which is fundamental for a sustainable change, but different barriers are hindering a shift from the business as usual to more sustainable science; even though multiple, already existing measurements could be applied. With each aspect relevant to the environmental impact of laboratories analysed individually, we could also distinguish the different facets of the underlying issues:

In terms of material and reagent use, the figures show a clear need for improvement. Data must be better collected and exhibit a greater availability so that resource consumption can be comprehensively documented, and the effectiveness of sustainability measures can be quantified simultaneously. The concrete figures make resource consumption more tangible and thus replace an abstract concept with clear, comprehensible data. The reuse of single-use materials exhibits a great potential for reducing their carbon footprint, and should be considered greatly [12].

In terms of devices, the data indicates the redundancy of devices in laboratories. Only a few devices are continuously in use during working hours. While the results clearly show that different specializations use equipment differently, further data collection will be necessary to have a stable basis for interpretation. Further research must be done on the actual use of equipment in laboratories and their consumption. While stand-by consumption, in general, is going to be regulated within the European Union from 2025 onwards by the Ecodesign for Sustainable Products Regulation (ESRP) on the broader policy level, various types of laboratory equipment is excluded from this regulation due to already intensive regulation issues within the branch. Considering sustainability in the use of devices one must differentiate between existing material to work with in contrast to straightforward planning processes, where new equipment is going to be procured. While the later one allows a thorough sustainability planning to avoid redundancies, overarching resource consumption and efficient placement within the laboratory, the majority of sustainable laboratory initiatives have a full set of equipment already at hand. Placement of existing equipment is of big importance, as it can affect processes as well as consumption. Laboratory freezers affected by sunlight on a daily basis increase overall consumptions similar to habits such as keeping the modern, energy efficient device as an offline backup for the old device, while that one continues to run 24/7. Redundancy of older equipment might provide a solution for end-of-lifecycle considerations, where one device can provide spare-parts for the other one, once the manufacturer service cannot provide the parts anymore. 3D printing for spare parts can be considered as an alternative for spare parts but is often questionable in terms of quality and risk management.

The procurement of sustainable products is generally desirable and the respondents’ desire for official seals to label environmentally friendly products is understandable in terms of transparency. However, there is a risk of greenwashing with labels and terms such as ‘green’, ‘eco-friendly’, or ‘all-natural’. The EU is therefore planning to regulate sustainable labels more strictly in order to inform and protect consumers. Sustainability claims will have to be substantiated and verified by independent bodies and comparisons made by companies must be transparent and comprehensible. Labels that do not offer any real added value should be avoided. Implementation of this directive will be mandatory for member states from spring 2026 [11]. To reduce transport distances and save on packaging material, bulk orders should (continue to) be favored. Before purchasing materials and equipment, it is advisable to opt for durable and high-quality options. These may initially be the more expensive option compared to other options, but in the long term will result in fewer new purchases having to be made. Conversely, an increase in demand for sustainable products can lead to a lower customer price [8]. Additionally, time resources can be saved by integrating sustainability into the pre-existing structures in the procurement process: central purchasing system at the university level (such as SAP) could include primarily sustainable and traceable alternatives, as well as a reference on emission export.

As for waste disposal, the recycling structures offer potential for improvement. While the disposal is regulated by the corresponding waste company, our study showed that there are still difficulties, i. e. if certain materials can be recycled or in which bin they belong, while others believed that even if they separate the waste, it will then be thrown together again by the cleaning staff. Hence, a closer dialogue between management and cleaning staff is favorable to fostering sustainable practices within laboratories. This can be done i. e. through training and sensitizing to sustainability for non-academic staff, which is often forgotten when it comes to HEIs and implementing changes [3].

While the respondents also identified the potential measurements that are needed to move forward, the barrier lies within the conditions and rigid structures of the HEIs. Initiatives from the staff and faculty members can for example exhibit great potential [5]. However, we observe a common problem within the sustainability movement – missing structures from the top that ensure the flourishing of grass-root and bottom-up movements [9]. The integration of sustainability should be at the core of the institution, ensuring that the concept is an integral part of the identity, and hence is not only considered in the reporting but also in every other managerial aspect. Thus, HEIs should implement this top-down steering to achieve more sustainable operations, ensuring effective implementation of sustainable operations and sustainable science [22].

Furthermore, motivated staff and students should be included in the decision-making to achieve more efficient and effective measurements. Combining bottom-up and top-down decision-making is not only effective in the sense of including all perspectives in the decision-making, but also makes the bottom-up movements heard and valued, potentially increasing their self-efficacy, which is essential to human behavioral change and motivation [4–17]. In the sense of Sustainable Development Goal 17 (Partnerships to achieve the goals) institutions could benefit greatly from working jointly and sharing best practices [4]. The motivational incentives should also be reflected in one of academia’s most wanted: funding. Funding agencies such as the German national research agency DFG have already committed and included sustainability of the research operation themselves within their funding guidelines [7], however, the broader implementation of it across all funders could greatly support the move towards sustainable laboratories.

Beyond that, the amount of responses that would wish for more information showcases that, one, the information is not available yet due to missing data on sustainability assessments, and two, that the information already existing is not accessible enough. Scrutinizing the study results into practical implications, we recommend a few measurements to aid the development of sustainable practices in German HEIs laboratories, as seen in Table 1. These measurements are exemplary, given that there are a variety of measurements depending on the respective area that is observed.

5. Conclusions

This study provides insights into the current state of sustainability practices within German university laboratories, offering both theoretical and practical contributions. For example, the findings demonstrate that laboratory operations, as resource-intensive hubs within higher education institutions, hold significant potential for advancing sustainable development. The theoretical contribution lies in uncovering the interplay between bottom-up initiatives and the need for institutional frameworks. While laboratory staff often take the lead in sustainable

Table 1
Exemplary, not exhaustive, possible Measurements for more sustainable laboratories.

Measure	Description	Benefits	References
Strategy and Management			
Sustainablility Strategy	Incorporate holistic sustainable thinking into the institution through i. e. a sustainability strategy that takes a whole-system approach	Consideration of sustainability in all aspects of operating, to be more effective and efficient	[19–23]
Stakeholder Engagement	Bring all stakeholders (academic and non-academic) together, promotion of sustainability initiatives and workshops	Increase awareness and participation in sustainability efforts, strengthen the exchange of information	[3–23]
Cultural Practices			
Motivational incentives	Establish motivational incentives in the form of public recognition or bonuses for people engaging in sustainability practices, one example could be to reinvest the saved money into the research department	Cultivate extrinsic motivation to complement the intrinsic one, leveraging behavioural change	[6]; [27]
Enhance Awareness	Train academic and non-academic stakeholders on sustainable laboratory practices, through workshops or/and by including sustainable practices in the curricula, including nudges into the laboratory environment	Foster a culture of sustainability within the laboratory, facilitate the change to environmentally friendly options	[3–10]
Certifications	Implement a laboratory certification	Enhance motivation by recognition, make progress more tangible	[24]
Resource Efficiency			
Energy Efficiency	Review which equipment, including lightning, etc., can be upgraded to energy efficiency, as well as using renewable energy sources wherever possible	Reduced energy consumption and costs, decreasing the carbon footprint	[1–18]
Waste reduction	Implement recycling programs, reuse materials wherever possible, rethink the size of experiments	Reduce landfill contributions and thus the environmental impact	[13]
Water conservation	Install low-flow fixtures, if possible, reuse cooling water	Lower water usage and costs	[10]
Green Purchasing	Order in Bulk, review alternative sustainable options,	Support environmentally friendly suppliers	[8,26]

actions, institutional support remains fragmented. Theoretical frameworks, such as social cognitive theory, could underscore the role of perceived institutional support and self-efficacy in driving sustainable behaviour, further enriching the discourse on behavioural and organisational change within the sustainability movement. In addition, the research highlights the importance of integrating environmental, economic, and social dimensions into laboratory sustainability.

This research also has practical implications, especially in terms of actionable areas such as reducing single-use plastics, optimising equipment usage, promoting recycling, and establishing centralised systems for data collection and sustainable procurement. Recommendations such as embedding sustainability into academic curricula, creating motivational incentives, and leveraging collaborative platforms for all stakeholders, whether academic or non-academic, provide a clear pathway for HEIs to transition toward more integrated and effective sustainability practices.

Apart from the findings, this research also has limitations, which could also generate ideas for future studies. The focus on German laboratories within HEIs may limit the generalizability of the conclusions to contexts with differing regulatory, cultural, or resource dynamics. Moreover, the reliance on self-reported data introduces potential biases, and the lack of centralised resource consumption data constrains the ability to comprehensively analyse laboratory operations. The diversity in laboratory settings and research activities also poses challenges in standardising sustainability measures, underscoring the need for context-specific strategies.

In the European context, there are organizations such as the Sustainable European Laboratories network (SELs) or national organizations such as GreenLabs-Austria or GreenLabs-Netherlands, where grassroot initiatives find guidance in facilitating own experiences and results. Due to differences in national regulations only some of theirs works can be seen as Best-practice examples for other countries like Germany. However, the struggle for more sustainable laboratory use is similar in all countries in Europe, due to similarities in curriculum content and standardized procedures of analytical chemistry within Europe.

Outside of HEIs, the field of analytical chemistry is a diverse area (e. g. for chemicals in surface water), where sustainable thinking and the scope of continuous analytics collide. While the aspects of sustainability (see Fig 1) indicate that the sustainable solution is not to have a laboratory at all, the necessity for analytics results in the need for agree on a balance between these colliding perspectives. Reconsiderations about process protocols, security measures and redundancy in processes could lead to an increase in sustainability without interfering with the need for analytics.

Despite these limitations, the study underscores the urgent need for HEIs to adopt a more holistic approach to sustainability, incorporating both institutional leadership and stakeholder collaboration towards sustainable labs. Also, the approach used here may be replicable elsewhere. Future research should explore mechanisms for integrating bottom-up and top-down approaches alongside strategies for improving data collection and monitoring systems. By addressing these gaps, HEIs can enhance their role as leaders in sustainable development, ensuring their operations align with the sustainability principles.

CRediT authorship contribution statement

Caterina Baars: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Patrycja Karwasiecka:** Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis. **João Henrique Paulino Pires Eustachio:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Conceptualization. **Andrea Dobri:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Jelena Barbir:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Conceptualization. **Sven Kannenberg:** Writing –

review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Walter Leal Filho:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sven Kannenberg reports financial support was provided by German Federal Environmental Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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All authors contributed to the study's conception and design. Baars, Eustachio, and Kannenberg performed material preparation, data collection, and analysis. Baars wrote the first draft of the manuscript, while Dobri, Barbir and Leal Filho commented on previous versions. All authors read and approved the final manuscript.

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Raw data for the dataset are not publicly available to preserve individuals' privacy under the European General Data Protection Regulation.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.greeac.2025.100288.

APPENDIX A

Fig A.1

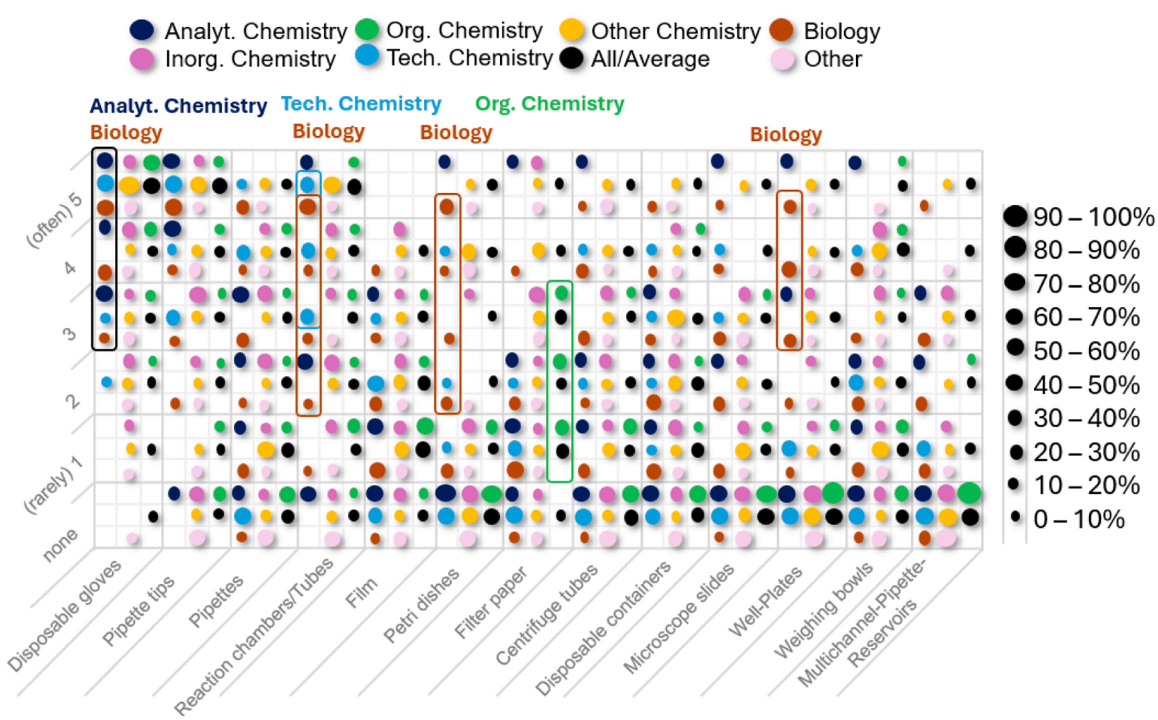

Fig. A.1. Use of different laboratory materials on average and by profession. The size of dots in each category represents the overall share (often to never).

APPENDIX B

3.1. Materials and reagents consumption

"Of course, the plastic lids are a bit more problematic, but even if they're still OK and most of them don't come into contact with the chemicals and solutions, we simply rinse them with ethanol and isopropanol and reuse them." (06)

"[…] the disposable syringes, we make sure that we always wash them between uses, so to speak, and then use them more often." (02)

3.3. Waste disposal

“We have all four bins, yellow, blue, black and white for glass and then, as I said, the one for autoclave waste. That’s separate.” (07)

“Waste separation is standardised and regulated everywhere.” (09)

“It’s similar to glass, laboratory glass. Every recycler is happy when they have a broken laboratory glass bottle in their recycling material, because they usually can’t be recycled like that.” (05)

“And exactly, the pipette tips cannot be recycled because they are microbiologically contaminated to a certain extent.” (01)

For us, as soon as you go through the airlock, everything is hazardous waste because we assume that everything is contaminated with lead.“ (07)

We work with GMOs or S1 organisms and try to use 70 percent ethanol in some cases, but for some decontamination we have to use another agent […], it is labelled as environmentally harmful, but we really try not to use very much […]. Then it goes into the autoclave waste and then I think probably into the residual waste. There’s no other way because, as I said, it’s contaminated organisms or surfaces.“ (07)

“So of course we have similar difficulties because, I have to say quite clearly, I’m not sure which plastic goods that we all use are recyclable at all if you were to dispose of them in the yellow bin if you could.” (05)

“I’m just wondering where polystyrene should go. That’s not entirely clear to me.” (07)

‘’This means that you can send them back after use and they are then reprocessed so that they can be used several times.‘’ (05)

‘’Well, the glass bottles are even recycled, they are cleaned again in an acid leaching bath after the solution is collected separately in inorganic and organic canisters. And the canisters are delivered to us, stored centrally in the meantime and then collected.‘’ (06)

3.5. Awareness

“But that’s not enough. You also have to have someone who can do it and make the working hours available for it and you also have to be paid accordingly. So of course it’s the money, but not just the money for material costs.” (06)

“You can, I think, but that’s my working time, I wouldn’t use it to do that now, because that’s also, well.” (09)

“We can’t change the big central processes as a little light in the lab. We talk about it, but it has to be decided by someone at the top. If nothing comes of it, then our hands are somewhat tied. We can only encourage […]” (04)

“Yes, for that we first need to know what. Where we could make savings. Exactly, where you can perhaps get information on what you can do better. And then you can see whether there’s any reason not to.” (07)

Data availability

The data that has been used is confidential.

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