ROYAL SOCIETY
OF CHEMISTRY

SUSTAINABILITY

Sustainable laboratories

A community-wide movement toward sustainable laboratory practices

GSK Carbon Neutral Laboratory for Sustainable Chemistry. Photo credit: University of Nottingham

Introducing our perspectives series

In a world where global challenges and advances in technology bring both uncertainty and new possibilities, the chemical sciences have a critical role to play. But what will that role be? How can we maximise the impact we make across academia, industry, government and education? And what actions should we take to create a stronger, more vibrant culture for research that helps enable new discoveries?

Our perspectives series addresses these questions through four lenses: talent, discovery, sustainability and research culture. Drawing together insights and sharp opinion, our goal is to increase understanding and inform debate – putting the chemical sciences at the heart of the big issues the world is facing.

Sustainability

Our planet faces critical challenges – from plastics polluting the oceans, to the urgent need to find more sustainable resources. But where will new solutions come from? How can we achieve global collaboration to address the big issues? And where can the chemical sciences deliver the biggest impacts?

Talent

Talent is the lifeblood of the chemical sciences. But how do we inspire, nurture, promote and protect it? Where will we find the chemical scientists of the future? And what action is required to ensure we give everyone the greatest opportunity to make a positive difference?

Discovery

Chemistry is core to advances across every facet of human life. But where do the greatest opportunities lie? How will technology and the digital era shape the science we create? And what steps should we take to ensure that curiosity-driven research continues to unlock new opportunities in unexpected ways?

Research Culture

Globally, scientific research in academia and industry fuels both progress and innovation. But how do we create more inclusive, diverse and vibrant environments for research, that lead to better, more open science? And how should we recognise the breadth and diversity of the people, contributions and achievements that enable new discoveries?

Find out more at **www.rsc.org/new-perspectives**

Foreword

Professor Gill Reid

Dr Helen Pain

Science creates remarkable discoveries and innovative technologies that will be key in achieving the UN Sustainable Development Goals. At the same time, scientific research is contributing to greenhouse gas emissions, plastic waste and other environmental issues.

This tension presents many challenges, as well as opportunities, for practising scientists.

Researchers are increasingly aware of the environmental footprint of their work and many individuals and organisations have made changes. But some are finding it difficult to take action – for all sorts of reasons. Some feel unable to influence change in their role, while others do not have the money, knowledge or data to implement more sustainable laboratory practices. There can also be resistance within leadership, or inertia among colleagues, to engage with the sustainability agenda. And yet laboratories must address issues like energy consumption and waste production if they are to become greener.

The flip side is that the chemical sciences community can be at the forefront of this multidisciplinary effort to optimise the environmental performance of laboratory buildings, processes and equipment. Scientific research, itself, is at the centre of creating more sustainable chemicals and materials. Developing and embedding sustainability best practice will empower individuals to make a difference. Driving lasting change will require strong leaders and sustainability experts, opening up opportunities for new job roles, professional development and innovation.

Over the past year, chemical sciences researchers (in the UK and around the world) gave us their perspectives on sustainable practices in the laboratory. It is clear that people care about this: 90% of those who took part in our survey agreed or strongly agreed that it is important to consider sustainability in their day-to-day work. However, there is an urgent need for more resources and new communities to support sustainable laboratory practices and to enable the necessary changes in everything from culture and digitisation to regulation and funding.

Our community is proactive and this report includes many examples of individual actions as well as from companies, institutions and funders. We hope that these will, in themselves, be useful to individuals and organisations who are earlier in the journey to make their science more sustainable. We are grateful to our survey respondents and all the members of our Subject Communities who initiated the thinking and participated in discussions for this report. Their contributions lay the foundation for our long-term ‘Sustainable Laboratories’ programme to help our community make their research more environmentally sustainable.

Gill Reid

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Helen Pain

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Key findings

1. There is a huge appetite on the part of researchers to reduce the environmental impact of their day-to-day scientific work, and the majority are already trying to do so.

- **79%** agree that they know how their actions in the laboratory impact the environment.
- **84%** agree that they would like to do more to reduce the impact of their day-to-day scientific work on the environment.
- **63%** have made changes in the last two years to reduce the environmental impact of their research activities, or those of their research group, team or department.

2. Researchers face complex and context-dependent challenges in making their research more environmentally sustainable. Decision making is influenced by geographical location, access to resources, scale of operation, and research field. Barriers and challenges include:

- organisational culture and attitudes
- time and money
- the availability of data, along with knowledge and expertise, to enable informed decision-making and prioritisation
- navigating the trade-offs between environmental sustainability and other factors including safety, health, regulation, cost and research or application quality
- 'wasted experiments' due to poor research design and reporting, as well as duplication of effort entailed in replicating unpublished studies.

3. There are many exciting opportunities to make science more environmentally sustainable and the RSC is committed to driving these forward ourselves and in partnership with other organisations. These opportunities include:

- enabling the development and sharing of good practice through communities and networks
- recognising and incentivising initiatives and attitudes that work in favour of sustainable research
- development of resources, education and training opportunities appropriate for people in different roles and at different career stages, from early career researchers through to technicians and research group leaders
- the creation of and support for roles wholly or partially dedicated to laboratory environmental sustainability programmes
- harnessing data and digital technologies to record and share sustainability-related data, and to optimise experimental design and execution
- supporting R&D to overcome scientific and technological barriers to sustainable research.

Our action plan

Our action plan to help our community move towards a future of more sustainable laboratories.

Making the way in which we work within the chemical sciences and across its collaborative interfaces more environmentally sustainable is a long-term endeavour. There won't be a one-size-fits-all solution, and positive change will necessitate the entire community working together towards this goal.

We will be supporting the community with a programme of initiatives over the long-term, and, as our initial contribution to these aims, we have committed to the following seven-point action plan.

1. **Recognise and reward**
   We will celebrate and incentivise actions and initiatives driving change towards more sustainable labs – through our prizes and wider recognition programmes.

2. **Provide resources**
   By maintaining a collection of resources and tools from a wide range of experts and sources, we will empower our communities to implement good practice and make informed decisions for their own research activities.

3. **Establish global networks**
   We commit to supporting our communities to share practice and knowledge, and we will create and enable networks and fora to enable practitioners to progress on their sustainability journey and support one another.

4. **Convene partnerships**
   We will harness the diverse expertise and experience of other organisations to build effective partnerships and collaborations including gathering data, establishing guidelines, and supporting the changes needed to move towards more environmentally sustainable laboratories.

5. **Advocate for change**
   We will continue to advocate for the needs of our science and our community, using our voice to influence funders, policymakers, publishers, educators and beyond, to the benefit of society.

6. **Fund sustainable laboratories initiatives**
   We will expand our existing programme that awards enabling grants to researchers to include support for initiatives that make research more sustainable.

7. **Embed sustainability in degree courses**
   We will continue to engage with industry, academia and other sectors to establish criteria for university chemistry degree accreditation that recognise the importance of embedding sustainability in degree courses.

1 Introduction

Science and technology are key to a more sustainable future in everything from tackling disease to developing clean energy technologies. Laboratories - in universities, research institutes, hospitals and companies - are essential to research, analysis and teaching. They often bring together several disciplines and involve different configurations and scales of wet, dry and computational facilities.

Laboratory buildings, processes and equipment, by their nature, can be resource and energy intensive. Safely carrying out high-quality research can require temperature control, ventilation or high sterility. The sourcing, manufacture and disposal of specialised laboratory consumables and instruments all have an environmental footprint.

For this report scientists working in academia, industry and education have shared their views on minimising the environmental impacts of research. They highlight what they are already doing, the trade-offs they need to manage, and challenges they face. There is a strength of feeling to do more and they also give views about practical solutions as well as opportunities for changes in the wider research and innovation ecosystem.

> **We hope that individual researchers who are starting to explore the environmental sustainability of their research will find the examples in Section 1.1 and Section 3 and the links in Section 1.2 a useful starting point.**

Photo credit: AstraZeneca

1.1 Environmental impacts of scientific research

Laboratories are found in a variety of locations and settings including universities, research institutes, hospitals and companies. They serve many different functions, such as research, analysis, and teaching, each of which can involve different combinations of wet and dry lab facilities as well as computation. A laboratory and the team(s) working in it are often part of an ecosystem including a wider research department, collaborators on-site or elsewhere, the use of shared measurement or analytical facilities, centralised procurement, as well as internal and external customers, funders and regulators.

In chemistry, and the many disciplines it interfaces with, research often relies on high energy use, water consumption, single-use plastics, reagents and solvents (see **Table 1** for examples).

While the environmental footprint of an individual laboratory may be small, in aggregate laboratories will be important in achieving comprehensive organisational and national net-zero targets. For example in the UK, universities increasingly report their energy consumption and carbon emissions.[1]

A recent analysis of the biodiversity footprint of the University of Oxford estimates that supplies and supply chains of lab equipment have much greater impacts on biodiversity overall than do international flights, the university's consumption of electricity or its use of construction materials.[2]

Laboratories have an environmental footprint. For example, energy is required to run equipment and to ventilate, heat or cool spaces and processes. There are also carbon emissions from consumables and reagents, and embedded carbon in instruments and equipment.

The accounting and reporting of direct and indirect carbon emissions using the Greenhouse Gas Protocol is based on three categories of emissions.[3]

- **Scope 1:** direct emissions such as from refrigerants, on-site electricity generation and gas consumption for heating.
- **Scope 2:** indirect emissions from energy directly consumed such as from electricity purchased from an off-site generator.
- **Scope 3:** indirect emissions across an organisation's whole value chain (for example, travel, laboratory equipment, chemicals, materials and waste).

Energy and greenhouse gas emissions

Laboratory energy consumption varies depending on the type of laboratory, area of research, building design, etc.

- An estimate from 2008 is that laboratories consume five to ten times more energy than an equivalent-sized office building. That figure can rise to as much as 100, for example for laboratories with clean rooms or high process loads.[4]
- A 2021 study found that median energy usage of laboratories is almost three times that of an equivalent sized office.[5]
- An analysis of London's university buildings found that building use was the strongest predictor of energy consumption, and that laboratories and workshops had the highest mean heating and electricity consumption, approximately double that of teaching and administration spaces.[6]
- The University of Oxford Environmental Sustainability Strategy, which includes a Sustainable Labs programme, estimates that laboratory buildings are responsible for around 60% of the university's total energy consumption and carbon emissions.[7] This is also supported by others who estimate that 60–65% of electricity consumption by a research institution is by its research spaces.[8]

Of the equipment contained within a 'typical' laboratory, fume hoods and ultra-low temperature (ULT) freezers are among the most energy intensive.[9,10] Measures such as closing the sashes of a fume hood can, in addition to being safer, reduce their energy consumption by 40% or more. Increasing the temperature setting of a ULT freezer to -70°C instead of -80°C can reduce its energy consumption by 30–40%. [11,12]

While small individual laboratories may have kW-scale electricity demand, some researchers also make use of large experimental facilities such as X-ray light sources, synchrotrons and high-performance computing clusters, which are highly electricity intensive. Power demands range from MW scale, consuming tens of GWh of electricity annually, upwards to hundreds of MWs in the case of the largest facilities such as the European Organization for Nuclear Research (CERN) which consumes approximately 2% of Swiss electricity.[13,14]

Air conditioning, as well as cooling and electrical insulation that support experimental equipment, produces an environmental burden directly from releases of fluorinated gases such as SF_6, PFCs and HFCs. For some larger instruments these can dominate emissions due to their high Global Warming Potential (GWP).[15] Regulations driving equipment manufacturers to phase out these gases, and innovations within experimental facilities, such as heat recovery and advances in superconducting magnets, can contribute to reduced direct emissions as well as greater energy efficiency.[16]

Water

Water is used for different purposes around the laboratory with its biggest use typically associated with cooling or washing.

- The University of Strathclyde, UK, estimated that, during the 2014–15 academic year, over 60% of its water usage was in laboratory buildings. It has taken steps to reduce this as part of its sustainable labs programme.[17]
- University-level data, collected as part of estates management, shows that water consumption is highest for research-intensive universities. For example, in the UK the Higher Education Statistics Agency publishes estates data annually.[18]

There are various approaches to reducing laboratory water consumption, such as:

- aerators on taps
- equipment that removes the need for water altogether, like waterless condensers
- devices and systems that use closed loops and recirculate water.

Many organisations have developed guidelines for their researchers to follow to reduce water usage in washing. Some organisations have strict protocols in place to handle safe disposal of laboratory wastewater. Larger organisations may have on-site wastewater treatment facilities.

Chemicals

Chemicals are widely used in laboratories, for example, reagents and catalysts, and solvents used in reactions for separations, analysis and washing. In addition to their carbon footprint and human health impacts, chemicals can – depending on how they are produced, used and disposed of – result in the pollution of air, water and soil.

There is extensive literature in the field of green chemistry, including for example the *12 Principles of Green Chemistry*, covering the development and application of more sustainable approaches. These include:

- the selection of more benign, less hazardous reagents and solvents[19,20,21]
- more efficient reaction design, including the use of more selective catalysis
- sourcing chemicals from renewable sources instead of being derived from fossil fuels.

'Greenness' metrics and toolkits allow chemical science researchers to evaluate the overall sustainability of reactions.[22,23] There are also commercially available online tools, databases and inventory management tools for keeping track of chemicals. These can help laboratories monitor use of chemicals and avoid over-ordering.

Single-use plastics

Single-use plastics are a source of environmental impact and material consumption within many research laboratories. Biological and medical laboratories tend to have a higher reliance on single-use plastics: for example, to carry out cell culture work or where there is a need for sterility.

Plastics used in laboratories include: polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), acrylonitrile-butadiene, poly [(mercaptopropyl)methylsiloxane] (PMMS), polymethyl methacrylate (PMMA) and polystyrene (PS). These materials, sometimes in combination, are found in products such as pipette tips, tubes, filter bottles, gloves, weigh boats, and well-plates, as well as in a wide range of packaging.

A widely quoted study from the University of Exeter, UK, estimated that, worldwide, institutions involved in biological, medical or agricultural research produce about 5.5 million tons of lab plastic waste per year: equal to around 2% of global plastic waste.[24] We were not able to find studies that were chemistry-specific.

Many research groups are sharing approaches to reusing some plastics which have resulted in less plastic waste and lower costs.[25,26] In addition, institutions are introducing guidance including:

- reuse, recycling and use of alternatives
- reducing packaging by buying in bulk when appropriate
- the use of supplier take-back schemes
- the design of experiments to use smaller reaction vessels.

Some universities have committed to completely cutting out single-use plastics across their institutions: for example, the University of Leeds by 2023 and University College London by 2024.[27,28]

However, it is not straightforward to replace all single-use plastic. Considerations such as convenience, time, cost and avoiding contamination are all key concerns. It is also not always easy for researchers to compare alternatives. In 2021, the UN Environmental Programme published life cycle analyses to evaluate the environmental performance of eight single-use plastic consumer products, such as cups and face masks, along with comparisons to their reusable alternatives.[29] We found just one analysis specifically of single-use plastic labware, comparing the CO_2 equivalent footprint of commonly used consumables for cell and bacterial culture with re-use scenarios. The study found that reuse scenarios resulted in a carbon footprint reduction up to 11-fold as well as similar or much lower running costs.[30]

Sustainable material resources

There is an increasing focus on the sustainability of the production and disposal of wider material resources: from inert gases to rare earth elements and precious metals. For example, national lists of critical raw materials are generally based on strategic economic importance and supply chain risks.[31] Some academic studies also include the environmental and social impacts associated with the exploration, extraction, processing and recycling of metals.[32,33] The United Nations Environment Programme has convened a 'Working Group on Transforming the Extractive Industries for Sustainable Development'.[34]

Metals such as cobalt, platinum and palladium are contained in catalysts. Helium is used for cooling: in Nuclear Magnetic Resonance (NMR) spectroscopy and MRI imaging (for example). It is also used as a carrier gas in Gas Chromatography/Mass Spectrometry (GC/MS) analysis.

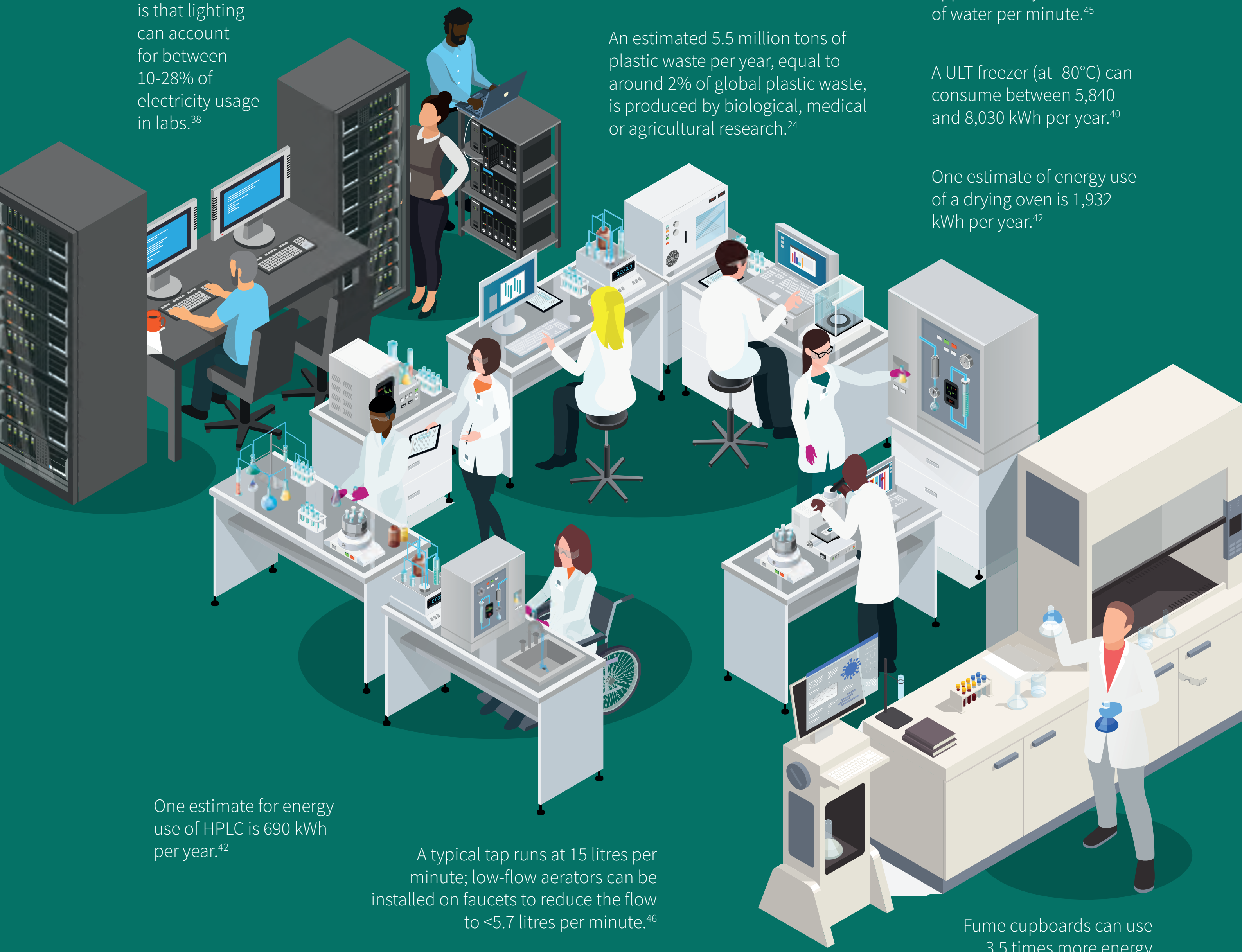
The increasing digitisation of research also carries an environmental footprint, although there are developments in areas like energy efficient computing and measurement hardware.[35,36] It will be important to consider the carbon footprint of running algorithms and of data storage. There is a need to weigh up the wider environmental and social impacts of electronics supply chains and e-waste.[37]

Examples of use within a laboratory setting

ENERGY	CHEMICALS & MATERIALS
Basic lighting, heating, air conditioning and ventilation	As reagents: chemicals for reactions, catalysts
Equipment such as fume hoods, ultra-low temperature freezers, hotplate stirrers, water baths, heating blocks, hot air guns, evaporator, furnaces/ovens, autoclaves, lamps, pumps, atmospheric purification fans, bio-safety cabinets, ultrasonic baths	As solvents: washing, flushing, separations and analysis (e.g. chromatographic purification)
Instruments (on a range of scales) such as benchtop microscope, mass spectrometers, HPLC, NMR, electron microscope, X-ray diffractometer, lasers	Helium (cooling and flushing)
Large facilities such as particle accelerators, e.g. synchrotrons or spallation sources and free electron lasers	Argon (for purging), nitrogen, xenon (lamps)
Computing, including personal computers, servers, cloud, high-performance computing, for data storage, analysis, modelling, simulations, graphics	Precious metals and rare earth elements as catalysts, in computers, and in instruments, e.g. indium is used as a reference standard for differential scanning calorimetry
	Other laboratory consumables such as paper for printing and recording results, cardboard packaging and needles
WATER	**SINGLE-USE PLASTICS**
Used for cooling reactions and equipment such as X-ray equipment, electron microscopes, gas chromatographers, mass spectrometers	Equipment, including vials, beakers, flasks, bottles, pipettes, pipette tips, syringes, cell culture plates, filters, test tubes, centrifuge tubes, cuvettes, weigh boats
Used for flushing/purging and washing laboratory equipment and also within a laboratory process	PPE e.g. latex/nitrile gloves
	Packaging

Table 1: Examples of uses of energy, chemicals and materials, water and single-use plastics in a laboratory setting.

Figure 1: Environmental impacts of scientific research: Examples of indicative usage by and emissions from laboratories. As a comparison, the medium Typical Domestic Consumption Value for electricity for a UK household in 2020 was 2,900 kWh per year .[41]



One estimate is that lighting can account for between 10-28% of electricity usage in labs.[38]

Training a large AI model can emit almost five times the lifetime emissions of the average American car.[44]

An estimated 5.5 million tons of plastic waste per year, equal to around 2% of global plastic waste, is produced by biological, medical or agricultural research.[24]

A vacuum pump uses approximately 15 litres of water per minute.[45]

A ULT freezer (at -80°C) can consume between 5,840 and 8,030 kWh per year.[40]

One estimate of energy use of a drying oven is 1,932 kWh per year.[42]

One estimate for energy use of HPLC is 690 kWh per year.[42]

A typical tap runs at 15 litres per minute; low-flow aerators can be installed on faucets to reduce the flow to <5.7 litres per minute.[46]

Direct releases of GHGs. Particle detectors at CERN emit fluorinated gases (CERN 2021), generating just below 200 kt of CO_2 equivalent emissions in 2017 and 2018.[43]

Fume cupboards can use 3.5 times more energy than the average US home.[39]

Note: usage and emissions will vary per lab, its uses, conditions and specific equipment.

1.2 Current initiatives, resources and mitigations

Setting targets and developing climate or sustainability action plans

There are net zero pledges covering 90% of the global economy with more than 700 of the largest global companies having set targets at some level.[47] However, My Green Lab found that while the largest companies have reduced carbon emissions, the majority of companies in the biotechnology and pharmaceutical industry do not have climate commitments aligned with a 1.5°C world.[48]

Efforts to support companies and organisations in setting targets and alignment to net zero include the Science Based Targets Initiative, a multi-stakeholder climate initiative.[49]

There are many examples of research-intensive companies that have set net zero targets alongside developing sustainability strategies. There are examples across chemistry-using sectors, including pharmaceuticals, biotechnology, consumer products, energy and agri-tech.

- AstraZeneca has a flagship Ambition Zero Carbon Programme which includes a commitment to have zero carbon emissions across its operations by 2025 and to become carbon negative across its value chain by 2030.[50,51]
- GSK has pledged to reduce emissions across its operations by 2030.[52] This includes targets related to water, waste and biodiversity. For example, it has pledged to have zero operational waste, including eliminating single-use plastics, by 2030.
- Unilever has emission reduction targets to achieve net zero across Scope 1, 2 and 3 emissions by 2039.[53]

According to the European Federation of Academies of Sciences and Humanities (ALLEA), there are currently no standardised emissions or environmental targets reporting schemes for university-based laboratories.[54] There are, however, various calculators, frameworks, and toolkits (see **Table 2**).

Many umbrella groups are convening their communities to set targets and to develop associated action plans. For example, Universities UK, encompassing 140 universities, has backed emission reduction targets. It has also outlined how it is responding to the climate emergency through its teaching, research, and leadership activities.[55]

Funders are also active. For example, UK Research and Innovation has an environmental sustainability strategy outlining the actions it will take to reach net zero for its own operations by 2040.[56] This includes embedding environmental sustainability across its investment decisions by 2025.

Building design

Many aspects of laboratory resource consumption are determined during building design.[57] Increasingly, both the public and private sector are embedding sustainable design into new buildings, including those used for research.

- AstraZeneca's Discovery Centre in Cambridge, UK, uses geothermal energy-saving technologies and energy efficient features. These will save enough energy to power 2,500 homes, ensuring that the building itself is environmentally sustainable.[58]
- Bristol Myers Squibb's biologics manufacturing facility in Devens, Massachusetts, was awarded Leadership in Energy and Environmental Design (LEED) Gold certification for its laboratory and administration building, and LEED Silver certification for its cell culture manufacturing facility.[59]
- GSK Carbon Neutral Laboratory for Sustainable Chemistry at the University of Nottingham has incorporated innovative technologies to cut waste as well as energy and water consumption of its research activities.[60]
- Harvard University's Science and Engineering Complex (SEC) has been certified by two international building certification programmes (run by LEED and Living Building Challenge) as one of the healthiest, most sustainable, and energy efficient laboratories in the world.[61] The building features high performance materials, novel technologies to ensure energy efficiency, and adaptable ventilation methods.

Networks, resources and organisational programmes

Many universities and companies have guidance, examples of good practice and case studies to support their researchers in becoming more sustainable.[62] These are often shared more broadly and, alongside various networks and resources, support sustainable research practice, advance best practice, and support the development of laboratory standards and certifications.

We have curated some examples in this report, and there are additional ideas and resources in **Section 3**. **Table 2** does not include the many resources being developed and shared by specific companies or institutions, but some of the initiatives listed signpost further or curate lists of resources.

Discovery Centre, AstraZeneca, Cambridge. Photo credit: AstraZeneca

Table 2: Examples of initiatives supporting the environmental sustainability of research.

Initiative	Brief description
Beyond Benign	Develops and disseminates green chemistry and sustainable science educational resources that empower educators, students and the community to practice sustainability through chemistry. https://www.beyondbenign.org/he-green-chemistry-commitment
Code Carbon	Open source software, compatible with Python, that tracks emissions associated with code execution. https://codecarbon.io
GES 1point5	An open source web application that enables research laboratories to calculate the carbon footprint of French public research. https://labos1point5.org/ges-1point5
Green Algorithms	A free-to-use research carbon accounting tool. https://green-algorithms.org
Green Impact	A framework developed by the UK's National Union of Students (NUS) for organisations to be environmentally and socially sustainable. It supports teams to embed the university's or college's sustainability strategy into everyday practices, provides online toolkits, monitoring and awards. https://greenimpact.nus.org.uk
International Institute for Sustainable Laboratories (I^2SL)	Engages stakeholders in advancing the safety and sustainability of laboratories and signposts tips, resources and benchmarking. It has adopted Laboratories for the 21st Century (Labs21), a former joint venture between the US Environmental Protection Agency and US Department of Energy. https://www.i2sl.org
International Sustainable Campus Network (ISCN)	ISCN aims to provide an international forum to support higher education institutions in the exchange of information, ideas and best practices for achieving sustainable campus operations and integrating sustainability in research and teaching. It awards ISCN Sustainable Campus Excellence Awards in three categories: Whole Systems Approach; Partnerships for Progress; and Cultural Change for Sustainability. https://international-sustainable-campus-network.org
Labconscious	An open resource and blog for the life science community to reduce laboratory waste, use green chemistry, conserve water and save energy. https://www.labconscious.com
LEAF	The Laboratory Efficiency Assessment Framework is a sector-wide framework developed at University College London to help improve sustainability and efficiency of laboratories including tools and standards for sustainable laboratory operations. https://www.ucl.ac.uk/sustainable/make-your-lab-sustainable-leaf
LEAN	The Laboratory Efficiency Action Network brings together members that work within laboratories or sustainability departments in publicly funded institutions. https://www.lean-science.org
Max Plank Sustainability Network	A grass roots initiative within the Max Plank Society bringing together scientists, technical and administrative personnel to improve cooperation and to develop less resource intensive scientific and day-to-day practice. https://www.nachhaltigkeitsnetzwerk.mpg.de
My Green Lab®	Resources to embed laboratory sustainability best practices including laboratory sustainability certification and signposting ways to reduce the environmental impact of laboratory processes. My Green Lab also supports the International Laboratory Freezer Challenge and ACT Environmental Impact Factor Label for laboratory products. https://www.mygreenlab.org
S-Lab	Primarily funded by the Higher Education Funding Council for England, this not-for-profit initiative is aimed at facilities, technical support and managers in laboratories. It supports improvements in the efficiency and effectiveness of laboratories, especially in universities and research institutes. http://www.effectivelab.org.uk
UNIDO Green Chemistry	A global green chemistry project from the United Nations Industrial Development Organisation (UNIDO) and partners to increase global awareness and deploy green chemistry approaches and technologies. Two of its main outputs are the Green Chemistry Guidance Document and Technology Compendium. https://www.unido.org/our-focus-safeguarding-environment-resource-efficient-and-low-carbon-industrial-production/green-chemistry
Examples of national programmes	Sustainable Labs Canada https://slcan.ca Green Labs NL (Netherlands) https://www.greenlabs-nl.eu Green Labs Austria https://greenlabsaustria.at

Research funder and publisher initiatives

The UN Sustainable Development Goals provide a common language to frame the actions that society needs to take to address global challenges. Funders, globally, are engaged with sustainability, which is increasingly becoming a desired impact of research investments by both government and charitable funders.[63]

The environmental sustainability of research itself, and broader aspects of sustainable research such as reproducibility and accessibility, are also a significant focus. For example:

- the US National Institutes of Health (NIH) Green Labs Program was designed to increase the awareness and participation of laboratory personnel in sustainable laboratory practices, with the goal of protecting the environment and human health. The program is adapted from My Green Lab to fit the circumstances and priorities of NIH laboratories[64]
- the Marie Skłodowska-Curie Actions Green Charter promotes the sustainable implementation of research activities in the context of the EU's flagship programme for the mobility and training of researchers[65]
- the Wellcome charitable foundation has a carbon offset policy for all travel deemed essential as part of the research it funds[66]
- Cancer Research UK's position statement on environmental sustainability of research sets out its commitments as a funder as well as its expectations of the research teams and institutions it funds.[67]

There is also some discussion about the use of environmental impact statements as a requirement for the submission of journal articles or grant applications. The Research Environmental Impact Disclosure used by the journal *Research in Engineering Design* is available more broadly as a means of prompting reflection by researchers while noting that the same template will not work for all types of research.[68]

Concerns about applying detailed environmental impact criteria to research grant proposals include adding additional administrative overheads and the challenges in creating criteria and evaluating against them.[69]

2 Attitudes to laboratory sustainability

Our survey shows that most researchers are aware of the potential environmental impact of their research and are taking steps towards reducing it. They also believe it is important to consider sustainability in laboratory work.

79%

agreed or strongly agreed that they know how their actions in the laboratory impact the environment

90%

agreed or strongly agreed that it is important to consider sustainability in their day-to-day laboratory work

84%

agreed or strongly agreed they would like to do more to reduce the impact of their day-to-day scientific work on the environment

63%

have, in the last 2 years, made changes to their own research activities, or those of their research group, team or department, in order to reduce the environmental impact of their work

We asked those respondents who are already taking action what motivated them **in addition to environmental sustainability**. 11% said they were required by their employer, 63% selected cost reduction and 58% said greater effectiveness or efficiency.

In the free-text survey responses we heard additional motivations including:

- laboratory health and safety, e.g. use of more benign as well as less or fewer toxic chemicals in reactions, reducing flood risk through alternatives to water cooling
- that it was "the right thing to do"
- influence from attendance at courses in, for example, green chemistry
- availability of funding to pursue research in more environmentally sustainable applications, e.g. the use of non-toxic or abundant chemicals
- sustainability related regulation of products and services
- customer and investor requirements.

3 What people are doing now

Many in our community are already taking measures to reduce the environmental impact of their work. They are also factoring in environmental sustainability at the research design and planning stages.

However, there is wide variation in the frequency with which people take these measures. It is also clear that there are numerous uncertainties, challenges and trade-offs in making these, and wider, changes. We discuss this further in **Section 4**.

Photo credit: AstraZeneca

3.1 Quantitative survey findings

	% respondents selecting **always**	% respondents selecting **often**
Day-to-day actions (Q11)		
Switch off equipment when not in use to save energy	44	35
Wash and reuse single-use plastics, packaging, or other laboratory disposables	17	22
Close fume hoods to reduce energy consumption	46	29
Share equipment with other groups/teams to minimise downtime	27	33
Consider energy impact of calculations/algorithms before running	9	11
Follow sustainability guidance or frameworks (e.g. LEAF, My Green Lab)	11	14
Measure the energy consumption of equipment to guide decision making	8	11
Purchase more efficient models of equipment	13	21
Reduce water consumption in the laboratory (e.g. using waterless condensers)	20	21
Research design and planning (Q12)		
Consider principles of green chemistry when designing experiments	18	25
Use solvent or reagent selection guides	20	23
Change reaction protocols to use less solvent or starting material	20	26
Use alternative, more environmentally benign solvents or reagents	20	27
Replace fossil fuel-based materials or chemicals with renewable-derived alternatives	11	17
Conduct risk assessment on environmental impact as part of project design	14	20
Recycling reaction components: for example, reagents, solvents or catalysts	14	18

Table 3: Q11 (n=620) and Q12 (n=618). Which of the following measures do you, or does your group, team or department use to reduce the environmental impact of your work? RSC Sustainable Laboratories Researcher Survey 2021.

The survey questions presented in **Table 3** were intended as a set of concrete starting points, but they might not reduce environmental impact in every situation. Some of the terms are not completely well-defined or some measures involve trade-offs and unintended consequences (see **Section 4**). This means they may not be more environmentally sustainable overall. For example:

- it is not always obvious without a life cycle assessment that one solvent is 'more environmentally benign' than another
- it is not possible or necessarily energy efficient to switch off certain types of scientific instruments regularly
- recycling can lead to impurities which compromise reproducibility therefore leading to more experiments and use of resources.

3.2 Qualitative survey findings

This section gives a more detailed picture of what scientists are currently doing. It draws upon the free-text and quantitative survey responses, as well as discussions with our member Subject Community Councils.

We hope that these are useful ideas for members of our community when considering the environmental sustainability of their research. It is, however, important to note that they:

- vary in scale, popularity and impact.
- are limited and generally within the control of an individual or small group. The wider set of changes people would like to make or see are discussed in **Section 5**.
- may not be the best option, a good option, or even an option, in every context. As discussed in **Section 4**, they may come with challenges and trade-offs in everything from health and safety or research quality, to cost, culture and lack of data to enable decision making.

3.2.1 Daily actions on energy, water, plastics and chemicals

Energy

- Close fume hoods.
- Optimise equipment and instrument settings, for example:
    - – on fume hoods, including automated control of variable flow or velocity
    - – raise temperatures of ultra-low temperature freezers, for example from -80 to -70 °C
    - – put computing and measurement instruments on standby mode if available and appropriate
    - – use switch-off timers for plugs for certain items.
- Regular inventory auditing.
- Freezer defrosting and clear-outs, including participating in ‘freezer clear-out challenges’.
- Monitor and report times for a reaction to complete in order to reduce resources used when the reaction is repeated (for example, report ‘seven hours’ rather than ‘overnight’).
- Switch off laboratory lighting and air conditioning when not in use and safe to do so; install LED lights and motion sensor controls.
- Reduce air travel, increase use of public transport for work travel and commuting.

Water

- Use alternatives to water-based cooling (for example, waterless condensers or coolant fans; rotary evaporator chillers).
- Install aerators.
- Reduce water pressure where it does not, for example, impact reaction efficiency.
- Being mindful of cleaning methods, for example use of pre-cleaning methods for glassware provided this reduces overall water consumption and associated disposal is environmentally benign.

Plastics

- Reduce the scale of experiments and therefore container size needed.
- Replace single-use plastic items with reusable items, typically glassware.
- Wash and reuse single-use plastics and packaging.
- Separate and recycle packaging and single-use plastic laboratory equipment using laboratory or organisational waste management programmes.
- Recycle PPE such as gloves via manufacturer take-back schemes.

Sustainable material resources

- Reduce solvent use (for example, in washing, chromatography and reactions) as much as possible.
- Inventory unused chemicals to enable sharing with other groups, for example using inventory management software.
- Recycle or repurpose solvents, chemicals, other reagents and catalysts in the laboratory.
- Procure recycled chemicals (catalysts, reagents, solvents).

Paper, cardboard, glass and needles

- Go paperless, including using electronic laboratory notebooks (ELNs) for writing up and recording data.
- Recycle paper, printer ink cartridges and cardboard packing materials.
- Repair and/or recycle broken glassware.

> “I regularly go through the labs and switch off equipment or close fume hoods and remind my students to do so too. On the other hand I keep machines running that should be running to keep their measurements reliable.”
>
> **Experienced researcher, Academia, China**

> “[...] we recently were successful in getting our Buildings Office to approve installing aerators to decrease water flow (and waste) throughout our research building. We have also started a programme of regular defrosting of freezers in our lab to save energy and inventorying unused chemicals to share with other groups to decrease waste and cost and save on storage.”
>
> **Early career researcher, Academia, Ireland**

3.2.2 Monitoring, sharing and procurement

- Conduct daily, weekly or monthly audits and routines related to energy, water, chemicals and waste.
- Monitor laboratory resource use to enable calculation of environmental footprint and the financial cost of different options.
- Donate old or unused equipment, instruments or consumables.
- Share equipment or instruments.
- Return unused chemicals to a centralised departmental store for reuse or share directly with other groups.
- Ask suppliers for validated sustainability credentials of equipment, instruments and consumables, covering a range of real experimental operating conditions or configurations.
- Change procurement processes and choices:
    - opt for more energy-efficient equipment or instruments
    - choose plastics that are more sustainably produced or biodegradable or both
    - use chemicals that are more sustainably produced
    - choose consumables with less packaging
    - switch from individual to group order systems
    - use centralised stock rooms or third party suppliers for just-in-time (JIT) inventory management
    - avoid over-purchasing by ordering exact amounts of chemical building blocks.

3.2.3 Research design, planning and reporting

Researchers gave examples of how they reduce the environmental impact through the design and reporting of their work. These fall into two broad categories:

Minimise 'wasted experiments' and maximise access to, and reproducibility of, research.

- Apply experimental design to minimise the number of experiments or steps in an experiment.
- Use computational modelling and simulations to reduce the number of physical experiments.
- Produce detailed documentation and reporting of results to ensure the wider community can access and reproduce experiments.
- Record and share negative results.
- Record and share data.

Embed environmental sustainability considerations in research projects and programmes.

- Follow sustainability frameworks: for example, Labs21, LEAF, LEAN, My Green Lab, NIH Green Labs, S-Lab (see **Table 2** for more detail).
- Consider principles of green chemistry when designing experiments.
- Conduct risk assessments on environmental impact as part of project design.
- Consider the carbon footprint of calculations or algorithms before running them.
- Use solvent or reagent selection guides (**Chem 21 solvent guide** and **ACS Green Chemistry Reagent Guides**, for example).
- Reduce the consumption of chemicals, plastics and energy where possible. For example:
  - reduce quantities synthesised
  - change reaction protocol to use fewer or less reagent(s) and less or no solvent (reduce the number of steps in a synthesis, for example)
  - use analytical methods and instruments requiring smaller sample sizes
  - use solvent-less techniques
  - use alternatives to high temperature processes (microwaves, plasma, mechanochemistry, for example)
  - use alternatives to high energy light sources or reduce duration of use (in photochemistry, for example)
  - ensure purity of starting materials to reduce the number of separation steps in analysis
  - replace fossil fuel based materials or chemicals with renewable-derived alternatives
  - switch from inert gases as carriers in gas chromatography where feasible and safe to do so
  - increase longevity of catalysts or use catalysts made from abundant elements rather than precious metals or rare earth elements.

3.2.4 Knowledge, skills and resources

Researchers currently get information about environmental sustainability from many sources. In our survey we asked people to select which, if any, sources they use. The top categories were:

- online resources
- journals and books
- my organisation
- my colleagues and/or my manager
- others in similar roles
- specialist staff in my organisation
- online training courses
- professional body.

In the free-text survey responses people also mentioned specific resources in addition to those given in Table 2:

- science magazines including *Chemistry World, C&EN, New Scientist*, and *Scientific American*
- supplier catalogues
- guides and resources shared by university departments: for example, the **University of Oxford's "A Guide to Reducing Single-Use Plastic"** or the UCL consumables and equipment guides.[70] (Visit **LEAF** for a detailed list)
- online seminars and events about laboratory sustainability. Examples include the Chemical Society of Nigeria Chemical Safety & Security webinars; the **RSC Net Zero Labs webinar**, and the **International Institute for Sustainable Laboratories** conferences
- professional communities like the **ACS GCI Pharmaceutical Roundtable**, **Beyond Benign**, the **RSC Environmental Chemistry Interest Group**, the **Biological and Medicinal Chemistry Sector** group, and the **Chromatographic Society**
- life cycle assessment tools and databases (**ecoinvent**, for example)
- general sustainability reporting frameworks and guides, such as the **Global Reporting Initiative (GRI)**, and the **Renewable Carbon Initiative (RCI)**.

3.2.5 Collaboration, culture and advocacy

- Establish laboratory culture where considering environmental sustainability is expected and normalised.
- Educate students and new laboratory members about sustainable practices.
- Draw on the skills and interests of new recruits to bring more sustainable approaches to laboratory culture and practice.
- Create a sustainability team within the research group.
- Seek certification and awards: for example, LEAF, LEAN, My Green Lab.
- Advocate within the group, department or organisation for more sustainable procurement, policies and priorities.
- Participate in departmental or organisational sustainability committees and advisory groups.
- Draw on knowledge and skills of research collaborators to identify and implement more sustainable approaches.
- Build skills and experience as part of research visits to laboratories with higher 'sustainability credentials'.
- Collaborate with internal sustainability experts and professionals: technicians, sustainability managers, sustainability officers, waste management experts, or colleagues with expertise in specific areas (chemical engineering, green chemistry, for example).
- Participate in informal networks of colleagues and peers to share knowledge and learning.

4 Barriers, challenges and trade-offs

We asked researchers about the barriers and challenges they face in making their research more environmentally sustainable. From literature review, discussions and free-text responses, it is clear that these challenges are complex and multi-scale. They involve interdependencies and trade-offs between different types of factors, including cost, data, expertise, research quality, culture, and safety.

The challenges that researchers face are also **context-dependent**:

- **environmental concerns and mitigation approaches are regional**, both within and between countries. For example, there is variation in the need for water conservation, the regulation of hazardous or other waste, the availability of recycling or renewable energy, government priorities and environmental sustainability policy
- **access to resources varies**, including money, expertise and knowledge
- **the scale of companies and research institutions varies**, as well as laboratories and research programmes within them
- **the type of research** also influences approaches to mitigation (research in a wet laboratory versus that which is conducted in computational or measurement facilities, for example).

The extent to which people consider different factors to be a challenge reflects a spread in experience and perspectives. At least 19% of respondents selected 'Neither agree nor disagree' for each of the options we suggested, with large proportions selecting agree and comparable proportions selecting disagree (see **Table 4**).

	% respondents selecting agree or strongly agree	% respondents selecting disagree or strongly disagree
I have not received any training	53	23
I am not able to influence policies or procedures within my lab/my organisation	30	45
I don't know where to start	29	49
There is not enough data available on which course of action is more sustainable	43	29
It is too expensive	29	35
I can make more of a difference by doing other things to reduce my carbon footprint	38	25
I struggle to find the time	42	29
There is currently no sustainable alternative to my current practices	28	38
I don't currently face significant barriers in implementing sustainable research practices	30	31
The building where I work cannot accommodate the equipment or measures I would like to use (for example, more energy and water-efficient equipment)	32	33

Table 4: Q15. To what extent do the following pose challenges to you in implementing sustainable practices in the laboratory? RSC Sustainable Laboratories Researcher Survey, 2021. (n=620)

“The challenge is so daunting and multidimensional that I think a lot of my peers feel overwhelmed and don't know where to start. We need to give people actionable information that allows them to make first steps. The sense I have is that in many cases it's "I didn't know that.." which leads to current practices continuing.”

Experienced manager, Industry, United States

“It would be useful to know more about more recyclable, reusable and/or suitably biodegradable consumables that are being manufactured that we could adopt. Even simple things, like eppendorfs, pipette tips and vials…”

Mid-career researcher, Academia, United Kingdom

“Structural aspects of basic and applied research need to be considered. It cannot be a simple minded 'turn off the lights when you leave' approach, or always use aqueous solvents. We need reliable audits on where our activities have the largest impacts and on which time scale.”

Experienced researcher, Academia, United Kingdom

“Lack of formal training and awareness of what our experiments do to the environment.”

Early career researcher, Academia, Kenya

“Cheaper and more convenient eco-friendly options. Sometimes we can’t choose what products to use as there are no options except to buy and use environmentally harmful products. There should be general procedure for re-usage of lab plastic equipment. For example, cleaning and sterilization can be more centralized. Now, it is just up to each laboratory to decide whether they re-use or dispose of lab plastic.”

PhD student, Academia, South Korea

4.1 Costs, careers and culture

4.1.1 Money and time

In the free-text responses and discussions, people frequently referred to direct and indirect financial costs as a barrier to developing and implementing sustainability-related changes in their research. They talked about cost at different scales, from the purchase of a single item, through to broader systemic issues about who should pay.

Here, we summarise the key points raised.

- **Macro-level economic models:** environmental impacts like climate change and pollution lead to costs in everything from replacing infrastructure and livelihoods to managing migration and health. In addition to moral considerations, this leads to macro-level questions about how to account for those costs and any savings or earnings from sustainability-related investments or initiatives. This question applies in general but also to the specific impacts of, and costs associated with, research.
- **Organisations, funders and cost recovery:** building a business case for investment in sustainability initiatives is influenced by internal processes and cost models. For example, a business case for an energy-saving initiative or waste management measures by one laboratory, department or function may lead to savings that later accrue centrally or to another part of the organisation (and vice versa). Similarly, if external funders pay for more sustainable options, then the associated energy or waste treatment cost-saving benefits may accrue to the research organisation rather than the funder.
- **Prioritisation of investment:** it is challenging to know how to channel finite time and money in a way that will deliver the most significant improvement in environmental footprint. Improvements may take or last a long time, and many actions have dependencies and unintended consequences. Prioritisation is a challenge at all scales: individual, laboratory, department and organisational. This is discussed more throughout this section.
- **Measuring and attributing the environmental footprint of research:** the use of resources and the generation of waste often changes throughout a research project or programme. Timescales can range from hours to months. In addition, large or multidisciplinary collaborations may be distributed over several laboratories, across different buildings and at multiple organisations. Each laboratory may be working on multiple projects for different internal and external customers, or funded by different external funders, or both. These factors make it challenging to measure a laboratory's environmental footprint, attribute it to individual projects, and develop cost models for reducing it.
- **Affordability:** sustainability related changes may simply be unaffordable in different contexts, such as small and medium-sized enterprises (SMEs) or resource-limited universities. This barrier exists across scales: from the costs of purchasing consumables and chemicals to longer-term investments in instruments, laboratory retrofits and new buildings or facilities. However, some sustainability related actions may result in immediate savings that can be reinvested to further enhance sustainability.
- **Pay-back timescales for large one-off projects:** big changes, from retrofits to new buildings or facilities, require upfront capital investment. It is not always possible to secure this investment even if an associated business case includes a model for return on that investment in the long term.

- **Funding for smaller one-off projects:** it is often unclear who might pay for smaller-scale changes. For example, the early replacement of benchtop instruments is typically not paid for centrally by a university or company but equally is not within the laboratory's regular operating budget model.
- **Funding for ongoing changes:** some sustainability-related changes simply cost more, directly and indirectly, on an ongoing basis and there may be no budget for this. Examples are buying smaller quantities or different types of chemicals, switching to bio-derived or recyclable consumables, or separating and recycling mixed waste streams.
- **Data to support financial decision making:** sometimes people do not have the detailed financial or environmental data needed to develop a business case or make a decision (see also Section 4.3 for more on data). For example, people may not know the actual energy consumption, costs or carbon emissions associated with an instrument they currently use, or those of an alternative instrument. This could be because: there are no or limited supplier specifications; they do not or cannot monitor their instrument use in detail; they do not know how to calculate associated carbon emissions.
- **The complexity of inter-laboratory cost-sharing:** even if laboratories would like to share instruments, some respondents are unclear whether funders and organisations permit this. In addition to sharing the cost of purchasing equipment, there are barriers related to the logistics, costs and responsibility for operating, maintaining and upgrading it.
- **The cost of developing and implementing sustainability plans:** many respondents indicated that they do not have the resources to pay internal or external staff to carry out activities such as:
  - calculating their baseline
  - researching more sustainable alternatives
  - developing sustainability plans
  - implementing sustainability plans
  - monitoring, reporting against and reviewing sustainability plans.

> **"Lack of sufficient funding to pursue the goal. For example, there are better and more energy efficient instruments I could use. However, since I do not have new funding to purchase such instruments, I need to use what I have."**
>
> **Mid-career researcher, Academia, United States**

> **“Working in a university, the only way to introduce more sustainable practices is to fund it myself and there are not research grants for this. The institution will not fund the changes we would like to implement.”**
>
> **Experienced researcher, Academia, United Kingdom**

> **“In many cases, capital investment is required in order to bring savings/sustainability/etc in the future. [...] In an industrial context, survival/profitability of the Company is the absolute top priority - and if that means no Capital Expenditure in the lab, we just have to carry on as best we can with what we've got.”**
>
> **Experienced chemist, Industry, United Kingdom**

> **“[...] Funding is also important to move to more sustainable sources and practices. A lot of financial investment is needed to replace the current less-efficient, energy-intensive equipment or practices in the laboratories.”**
>
> **PhD student, Academia, India**

4.1.2 Roles, careers and pressures

In their free-text responses, researchers expressed concerns about what is holding them or colleagues back in being more sustainable in the laboratory.

- **Sustainability is not core to roles or objectives:** even if they might like to do more on sustainability, they cannot make time for it within their current role.
- **Lack of sustainability expert roles within the organisation:** while some organisations have built up a degree of knowledge or have in-house expert roles, such as sustainability officers, managers or technicians, some people have no access to a sustainability professional from whom they can seek advice. (See also **Section 4.3**)
- **Time on sustainability is detrimental to projects, performance and careers:** project or publication timelines mean people cannot ‘afford’ to try alternatives and are more likely to stick with what they know works to deliver a result. For example, validating a new process takes additional time and delays or poor quality samples may result in project delays or failures. It can also lead to a loss of, or wasted time at, scientific facilities. These issues are present in both universities and companies with some variation in the reasons:
    - PhD students or postdocs are under pressure to get results so they can graduate or find their next role
    - early career researchers in academia may be under pressure to deliver results so that a Principal Investigator (PI) can publish, or so that they have a strong CV when applying for roles or a promotion

  - researchers at Contract Research Organisations (CROs) may need to meet client deadlines
  - researchers in one laboratory in a large company may need to meet milestones as part of wider R&D programmes. This could affect project success or failure and company or project profitability
  - research may be slower to deliver results, so researchers lose competitive advantage for themselves, their groups or employers. For early-stage SMEs, loss of time may result in the company failing.
- **Performance review and career incentives do not include sustainability:** recognition and progression for researchers are often based on project delivery and outputs that do not include sustainability related elements. (See also Section 4.1.3)

"Established protocols are hard to overcome when time-consuming searches of new protocols are not in and of themselves rewarded."

Experienced head of department, Academia, United States

"Currently, sustainability is not discussed as much as health and safety. This needs to change. As we raise the profile of sustainability it will become more a part of everyday work. At present other drivers, eg cost and quality, feel stronger calls to action."

Mid-career scientist, Industry, United Kingdom

"Evaluation of alternative approaches is time consuming and takes resource. As a small company this is hard to justify when staff are working hard just to keep the company afloat. Availability of external advice would be valuable."

Experienced manager, Industry, United Kingdom

4.1.3 Culture and mindset

Attitudes and culture were major themes throughout the free-text responses. Several themes emerged.

- **Individual or group inertia as a barrier to change:** respondents wrote about how people have to get over a natural initial 'activation barrier' to make a change. This barrier applies even if they know or believe that, in the longer term, a change may save time or money and be 'more environmentally friendly'. For example:
    - upfront or one-off investment of effort is required to research and procure alternatives, validate new processes, learn new ways of working or convince and help colleagues
    - some actions, while relatively straightforward, involve new habits or tasks that take more time or are less convenient (examples include closing fume hoods, using less water, switching off lights, and separating waste streams).
- **Resistance by organisations and senior leadership to engage with a sustainable laboratories agenda:** some people talked about active resistance to sustainability-related changes based on:
    - sustainability is not an organisational priority
    - lack of organisational, departmental or laboratory-level support for projects or research that will not deliver a publication or product
    - the perception that 'small actions at the scale of one laboratory make no difference'
    - co-workers or senior colleagues and managers in academia and industry do not personally care about sustainability or consider it relevant to their projects.
- **Concerns about the trade-off between sustainability, quality and impact:** some researchers expressed concerns that focusing on environmental sustainability in early-stage or discovery research may limit the quality and impact of research, or lead to inefficiencies in achieving impact:
    - large-scale potential applications of their research, especially in sustainability-related areas, mean that it is inefficient to invest time and energy in minimising the environmental impacts of their research process
    - imposing environmental constraints on early-stage or discovery research may result in missing breakthroughs that will deliver sustainable applications or products that far exceed the environmental footprint of the early-stage research
    - focusing at an early stage on something that appears to be environmentally sustainable may not provide a sustainable outcome when scaled up
    - research quality outweighs all other considerations.
- **Lack of incentives and rewards:** sustainability-related behaviours and initiatives by researchers are not universally encouraged or recognised within organisations or the wider research ecosystem, including funders, publishers, professional bodies and prize programmes. (See also **Section 4.1.2.**)

"The singular lack of insight around the 'big picture'. No one wants to spend a little money (in setting up procedures/processes/alternatives) to save a lot, as the saving is rarely instantaneous. There needs to be a collective understanding and promotion of that to the wider public that costs will have to go up for various things but that overall costs (eg pollution and similar) are likely to go down."

Experienced consultant, United Kingdom

"In our case, switching to a free-cooling system instead of air conditioning would greatly reduce environmental impact, but I personally have little power to introduce any changes in that direction."

Early career researcher, Academia, Spain

"There are some things that technically we cannot change of course, but as creative researchers we can always find some way to optimise our practises. I find that the biggest barrier to more sustainable research practises is not technical but a lack of practical support/awareness/logic at an institutional level."

Early career researcher, Academia, Ireland

"My group and I do always consider the principles of green chemistry, but our emphasis is on developing green processes for application at scale in industry, rather than on minimising the direct impacts of our research."

Early career lecturer, Academia, United Kingdom

"If something depends on me I definitely do it but some things I cannot change as my supervisor has control over them. And it's hard to change my coworkers."

PhD student, Academia, South Korea

4.2 The design, reporting and reproducibility of research

Researchers highlighted several barriers and challenges in this area:

- **Experimental planning and design:** not all research groups or programmes embed robust experimental design principles at the conception and design phase to optimise their experimental programme. This is partly due to culture and lack of awareness, as well as lack of access to training, skills and expertise in Design Of Experiments (DOE) and statistical methods and applications.
- **Embedding environmental sustainability in research design:** not all research groups or programmes consider environmental sustainability from the get-go or it is deemed peripheral to their research programme. This is partly due to culture and lack of awareness, as well as lack of access to training, skills and expertise in subjects like life cycle assessment, sustainability decision-making and reporting, and green chemistry.
- **Tensions with research efficiency and focus:** sometimes there are steps in a research programme that are a prerequisite for a new study. When this is the case, there are concerns that the focus is on completing the prerequisite steps as quickly and reliably as possible. This means there are even fewer motivations or rewards for making the prerequisite steps more environmentally sustainable.
- **Research reporting, reproducibility and data:** this is a complex area. It is linked to competition and intellectual property (IP) as well as systems and funding models for sharing research data and knowledge. However, a recurring and strongly expressed theme in the free-text responses was ‘wasted experiments’ due to:
    - poor-quality publications – for example, missing key pieces of information or data, making it impossible to reproduce an experiment
    - negative results – few outlets or incentives to share negative outcomes, resulting in duplication of effort as people repeat research that has already been done
    - data sharing – few outlets or incentives to share data so that other people could learn from, validate and build on it
    - code sharing – few outlets or incentives to share code so that other people can learn from, validate, improve and build on it.

> **“In my own research, which has involved synthetic lab work, the goal has generally been to get hold of the target molecule as easily/quickly as possible so that it can be used in further studies. Syntheses are often one-offs rather than a process that is going to be repeated on many occasions. Therefore coming up with a sustainable route has not been a major driver in synthesis planning and choice of conditions.”**
>
> **Mid-career researcher, Academia, United Kingdom**

4.3 Data, knowledge and expertise

Researchers' understanding of environmental sustainability and how to apply it to scientific research varies. Many participants in our survey and discussions raised issues related to:

- their own knowledge and skills
- access to the expertise of others
- the availability of data and knowledge needed to inform sustainability related decision making.

And we saw differences in the extent to which people have been offered and taken training, or believe that a lack of training is a challenge for them in terms of implementing sustainability-related changes.

There is also a range in the degree to which researchers have access to the expertise of others. Some have colleagues who are sustainability experts, while others cannot find, or afford, expert advice from outside their organisation.

In the free-text responses, people gave many examples of areas where they are aware that they, or someone else, need more data, guidance or information to inform decisions. This data or information must be combined with the skills to collect and use both. Here are some example questions.

- **Baseline and benchmark environmental footprint:** how do we calculate the current carbon and wider environmental footprint of our laboratory and what should we benchmark against?
- **Life cycle assessment:** when, and at what scale, is life cycle assessment appropriate and proportionate to enable decision making, eg to assess the environmental impacts of all stages of the life cycle of a specific piece of equipment, a chemical, an experiment or a specific research project/programme, full laboratory or department/facility, or certain time period?
- **Primary data:** when should we measure and record primary data, and when are models or approximations enough?
- **Waste management:** what are the different end-of-life and waste management options for different chemicals and materials? What are the associated environmental and cost implications of each?
- **Procedural or equipment alternatives:** what alternative processes, procedures, or equipment exist that we could use instead of existing methods or equipment? Where can we find the comparative data?
- **Procurement alternatives:** what are the available alternatives that we could procure?
- **Supplier sustainability claims:** where they exist, how can we validate supplier sustainability claims about the equipment and consumables we use in a range of modes or circumstances?
- **Cost implications of alternatives:** what are the cost increases or decreases associated with different consumables, instruments and equipment, infrastructure changes, and end-of-life options?

- **Health and safety implications of alternatives:** what are the health and safety benefits, risks and mitigations associated with different consumables, instruments, equipment, infrastructure changes, and end-of-life options?
- **Holistic options:** how do we know what other laboratories or parts of our organisation are doing? Are there opportunities to consolidate efforts and avoid duplication? Can we change our local sustainability priorities to have a greater impact, or use available resources more effectively in light of the organisation-level picture?

"I can think of many cases where we thought we'd made a positive change to the sustainability of a process, only to have then dug deeper and found that the 'improvement' was actually worse because we didn't fully understand the source or fate of one of the reaction components."

Experienced manager, Industry, United States

"Measuring water consumption, energy consumption of individual reactions or labs is currently difficult. If we could do that it would be useful for scaling up and downstream processes[...]"

Experienced scientist, Industry, Switzerland

"Currently, manufacturers and suppliers do not provide useful information or solutions. [...] We are considering changing the setting [on an Ultrafreezer] from -80 to -70 degrees C, but manufacturers do not provide energy usage of their freezers at both temperatures, so the savings in energy is not easily quantifiable."

Experienced researcher, Academia, Netherlands

4.4 Infrastructure, procurement and organisational policies

Researchers highlighted various challenges in making changes that arise from higher level organisational processes and structures. These overlap with some of the themes above. Many commented that these issues are not straightforward to solve due to the multi-scale and complex nature of sustainability-related decision-making and action.

- **Infrastructure:** laboratories are usually housed within larger or multi-use buildings and this limits the extent to which sustainability-related changes can be implemented. For example, it may not be possible to:
    - switch to alternative electricity providers
    - install equipment or instruments that are compatible with building ventilation, heating or cooling systems
    - create spaces for shared equipment.
- **Centralised procurement and stores:** these can limit the ability of a laboratory to identify and switch to alternative suppliers. For example, there may be preferred supplier agreements, long-term contracts with suppliers, or resistance within procurement teams to make changes.
- **Centralised waste management:** certain waste and recycling options may not be available, are unclear, or are not facilitated in a way that is compatible with laboratory waste streams. This ranges from the availability of plastics, paper and cardboard recycling, to the separation and disposal of different types of hazardous and non-hazardous waste, including chemicals. A particular challenge is how to handle mixed hazardous waste (for example, a plastic syringe and steel needle containing a chemical or biologic waste).
- **Communication and understanding between functions:** sometimes sustainability-related decisions made centrally are incompatible with local laboratory conditions. One example was where a centralised initiative to conserve water by reducing water flow resulted in a research group purchasing and using pumps to increase water pressure to the level required to cool reactions safely. In another example provided, all chemistry department waste is labelled as 'biohazard' or 'chemically contaminated' even though most of the waste is neither and so could be handled differently.
- **Coordination and efficiency:** as discussed in Section 4.3, there are challenges in accessing information and expertise, and in coordinating across departments, sites and functions within an organisation.
- **Cost allocation:** there can be a lack of clarity about where responsibility lies for bearing costs and to where the benefit of cost saving accrues. This can happen within an organisation and between the organisation and external funders.
- **Shared equipment and roles:** sometimes policies related to equipment sharing and support for operation and maintenance of equipment are unclear.
- **Influence:** some researchers expressed frustration that they feel they cannot influence more central or higher-level decision-making with regard to all of the above.

> **"Waste management and recycling must be improved at my institution. There is virtually no guidance in terms of sustainability and the responsibility falls to research groups which have to face more paperwork and assess the environmental impact of their projects without any previous training."**

Early career researcher, Academia, Spain

> **"I would like to share more equipment, however I will not do this where I am responsible for the training and maintenance costs. Long term funding for technical staff would be essential. Not normally available through institutes or funding bodies."**

Experienced researcher, Academia, Australia

4.5 Technical challenges and trade-offs

4.5.1 Safety and regulation

Survey participants emphasised the importance of safety within the laboratory and also for consumers. They raised some of the trade-offs with achieving environmental sustainability.

- **Standard protocols and regulated processes:** many sectors, such as food, biotech and pharmaceuticals, are heavily regulated.[71] Therefore, it is often impossible to change protocols or product licences without approval or re-accreditation by the associated regulator, such as a medicines or food standards agency. Many industries have standard procedures associated with regulation or existing large-scale manufacturing. This means that researchers need to follow those procedures for their research to be relevant to that sector.
- **Researcher safety:** ensuring researchers are safe is essential and requires the use of energy and other resources, for example:
    - sufficient laboratory lighting and ventilation, as well as water, detergent and solvents for purging and washing
    - PPE with a level of robustness or sterility (or both) depending on the ambient environment and substances being handled
    - the use of fume hoods and gloveboxes
    - reaction temperature control. An example is the use of dry ice or liquid nitrogen and solvent cooling baths to prevent runaway reactions.

> "There are some technological factors. For example, we make lithium battery electrodes and to a large extent we have to follow industry procedures in order to make our results relevant. Some of these procedures use materials that pose an environmental and health risk. They do eventually change just rather slowly."

Experienced chemist, Government, Australia

> "In a regulated industry it is difficult to make changes without regulatory requirements being used as a barrier to change."

Experienced consultant, Ireland

> "Once methods are developed, accredited and are run routinely, they are likely to run as is for the next 5-10 years without change; as we would need to re-validate."

Experienced manager, Industry, United Kingdom

> "Reusing materials is not really an option. Biological contamination means most consumables have to be incinerated."

Experienced manager, Industry, United Kingdom

4.5.2 Current science and engineering barriers

Researchers talked about multiple ways in which seeking more sustainable alternatives to current research practices is challenging.

- **Alternatives do not currently exist or are impractical, for example:**
    - there are reagents or solvents that cannot be replaced effectively by 'greener' alternatives, or cannot be manufactured more sustainably, or precious metal catalysts, such as palladium, for which more effective alternatives do not currently exist for certain classes of reaction
    - some specialised instruments are only available from one supplier, or they cannot be switched off regularly due to calibration times. The shut-down and start-up procedures also incur time, materials, and energy costs
    - some processes can only run at high or low temperatures, with high voltages, under increased or reduced pressures, or in regulated atmospheres.

- **Research quality is compromised, for example:** there may be impurities in recycled solvents, catalysts or reagents. There may also be differences between traditional and renewable-derived solvents leading to wasted experiments. The reuse of gloves, plastic vials or assay trays can mean that results or processes are not reproducible.
- **The product or process is not accepted by customers:** some customers require benchmarking against previous results and so will not accept results using a new protocol for synthesis or analysis. Customers may also not accept or be able to accept a lower quality or less reliable product (for example, if impurities are present).

"Recycling of materials in an analytical context can introduce additional environmental costs such as increased solvent washing/conditioning so we focus on Reduce and Replace more than Recycle."

Experienced chemist, Industry, United Kingdom

"Another challenge was no suitable substitutes were available or viable (instrument or chemicals or other consumables), this included inferior quality of alternatives eg contamination, misleading results, poorer performance. […] Quality of more sustainable alternatives (eg recycled solvent or more energy efficient instrument may not be as good scientifically)."

Experienced manager, Industry, United Kingdom

All in all, the picture that emerges is one of huge complexity. People give many examples of questions that are not easy to find answers to. These range from specific daily decisions or investment choices, to larger-scale instrument and research design choices, to high-level prioritisation.

In my specific context, and considering the interconnected dimensions of environmental sustainability, safety, financial cost and research quality…

…should I…

Figure 2: Examples of questions, choices and decisions related to laboratory environmental sustainability.

Sterilise glassware in an autoclave or use and recycle single-use plastics?

Use water or other solvents, like ionic liquids?

Use a high-temperature inorganic catalyst or a lower-temperature bio-based catalyst?

Use glassware and wash it with solvents or detergent, or use and recycle or discard single-use plastics?

Purchase a new, more energy efficient piece of equipment or use our existing equipment for longer because of its embedded carbon and the footprint of disposal of e-waste and other types of waste?

Do an experiment at a smaller scale with a consequence that the recycling of chemicals is not feasible, or do an experiment at a larger scale and recycle chemicals?

Do a wet laboratory experiment or run a computation?

Prioritise the time and money I have to invest in sustainability to:

- develop expertise in sustainability myself
- develop sustainability-related content for induction or training for laboratory members
- hire someone with sustainability expertise or advocate for greater departmental, organisational or systemic support for sustainability
- engage with chemical or instrument suppliers on the development of more sustainable instruments?

Refit or partially refit my laboratory or wait and advocate for a new building?

Switch a piece of equipment on and off or leave it running continuously with automated switching to standby mode?

"The issue of whether replacing old kit with newer more sustainable kit is actually more sustainable? Should we wait until natural 'end of life' for kit or should we act sooner in the hope of longer term gain versus greater amounts of eWaste."

Mid-career lecturer, Academia, United Kingdom

"We are a relatively small organisation, the timescales and pressure on the projects we run mean that there is limited possibility to pause, change processes, and implement new ones in particular as high purity of materials is all important. We can't afford not to make fast progress ... We have also made some changes to solvents to be greener but other attempts fell short as the replacement couldn't deliver the same results."

Mid-career manager, Industry, United Kingdom

"I work in a biochemistry setting with samples that are sensitive to contamination/degradation and there is little information/evidence about how to have a sustainable lab that does not impact the quality of these samples."

PhD student, Academia, United States

5 Opportunities and what needs to happen

There is no simple answer to the question 'how do we make research more environmentally sustainable?' As we have explored in this report, an evaluation of what is more 'environmentally sustainable' is often not straightforward. The question itself could apply at the level of an individual researcher, the work done in a whole laboratory, a large research programme, or research performed globally.

A more environmentally sustainable option may bring benefits in terms of costs, revenue, research quality, health and safety. But there are often trade-offs with these factors, especially in the short term.

However, it is clear from our researcher survey and discussions that researchers are aware, taking some action already, and want to do more.

We asked researchers what they think would help them in making their research more sustainable.

The ideas they shared were wide-ranging: from support for individual researchers to opportunities for more systemic change. This reflects the complexity, interconnectedness and multi-scale nature of sustainability.

In the following sections we draw out opportunities based on our research, what we heard in discussions with expert groups, survey results, and earlier insights from our ***Science Horizons*** and ***Digital Futures*** reports. Many of these are interdependent and mutually supporting. The scope for change provides an exciting landscape of opportunities for individuals, departments, organisations and the wider research ecosystem.

5.1 New communities and networks

In addition to those that already exist (see Section 1.2), many respondents to our survey talked about the need for new communities and fora. These would be useful at a range of scales, from small groups to larger fora. And they should be relevant in different ways to people: for example, depending on their level of expertise, or where they are in their sustainability journey. The purpose of these communities and networks would be to:

- share experience, good practice and knowledge about developing and implementing sustainability programmes, including sharing lessons learnt and practical examples
- develop good practice, discuss live sustainability choices as well as identify common needs, challenges and collaborative routes to addressing them
- create resources to enable the community to develop and implement sustainability initiatives or to support planning in their individual work, their laboratory, research programme, department or organisation
- raise awareness about sustainability and the options for those early in their sustainability journey.

These communities and networks could be organised around:

- co-workers and colleagues, noting the importance of proximal peer-to-peer learning and collaboration
- people from different organisations and sectors who have similar levels of expertise, experience and responsibility
- connecting people with others who have more or different types of expertise and experience
- connecting people in similar contexts and with similar challenges and options: for example, those working in similar research fields, in a particular region or organisation.

> **“Training and access to events/expertise would be helpful, in order to introduce sustainable practices to the whole institute instead of just the small group of us who are interested in implementing sustainable changes.”**
>
> **Early career lab manager, Academia, United Kingdom**

5.2 Education, training and professional development

Many respondents talked about education and training for themselves, their students, teams and organisations. This spanned undergraduate curriculum through to training as part of technical or research work and continuing professional development. Survey respondents also talked about the importance of informal or 'on-the-job' training and learning from colleagues.

Awareness, attitude and mindset

All researchers

General knowledge and skills

Ranges from basic to deeper knowledge and skills, including when to ask for and how to use expert input

Expertise, specialisation, innovation

Technicians, labs managers, sustainability professionals, green chemists, instrument developers and other specialists.

Figure 3: Systemic change requires a shift in mindset, increased skills and knowledge, and experts who can advise others and develop solutions.

When asked whether they have access to 'formal training on sustainability principles in research work', 56% of respondents to our survey selected 'none offered'.

Again, the needs and options for training reflect the various levels of experience a person has. It will also depend on the type of role they may have in considering, developing and implementing sustainability initiatives.

- **All researchers:** education and lifelong learning are essential to ensure a basic level of awareness and competence regarding sustainable research. These include: environmental sustainability concepts; experimental design and statistics; research integrity and ethics; and computation.[72]
- **Undergraduate students:** sustainability knowledge and skills, and experimental design and statistics, need to be embedded in the education of all students.
- **PhD students and postdocs:** early career researchers need to develop an awareness of, and competence in, applying sustainable research design and implementation skills. This will require varying levels of input from, and collaboration with, experts.
- **Research programme leaders:** leaders of research teams, functions and facilities need the skills and knowledge required to drive change in the environmental sustainability of their programmes or function. Training and development should include: technical aspects as well as support and shared learning in areas like championing, advocacy, leading change, the recruitment of, and collaboration with, people from other disciplines.
- **Research sustainability professionals:** individuals with particular responsibility for developing and implementing laboratory sustainability require education, training and CPD opportunities.

Respondents gave additional suggestions including:

- **different types of training**, including online and in-person, practical training based on real-world contexts
- **formal and informal learning and training**, especially learning from colleagues and collaborators
- **training in a variety of topics**, including:
    - technical areas such as green chemistry, life cycle assessment, or socio-techno-economic analysis
    - change management
    - skills to evaluate the challenge and decide, for example, when life cycle assessment or primary data is needed
- **incentivising training**, through grants and professional development recognition, for example
- **reinforcing training**, for example, by providing follow-up access to resources, tools, networks and workshops.

> **“I undertook an energy efficiency and green chemistry course which motivates my choices.”**
>
> **Early career researcher, Academia, Kenya**

5.3 Data, knowledge and tools

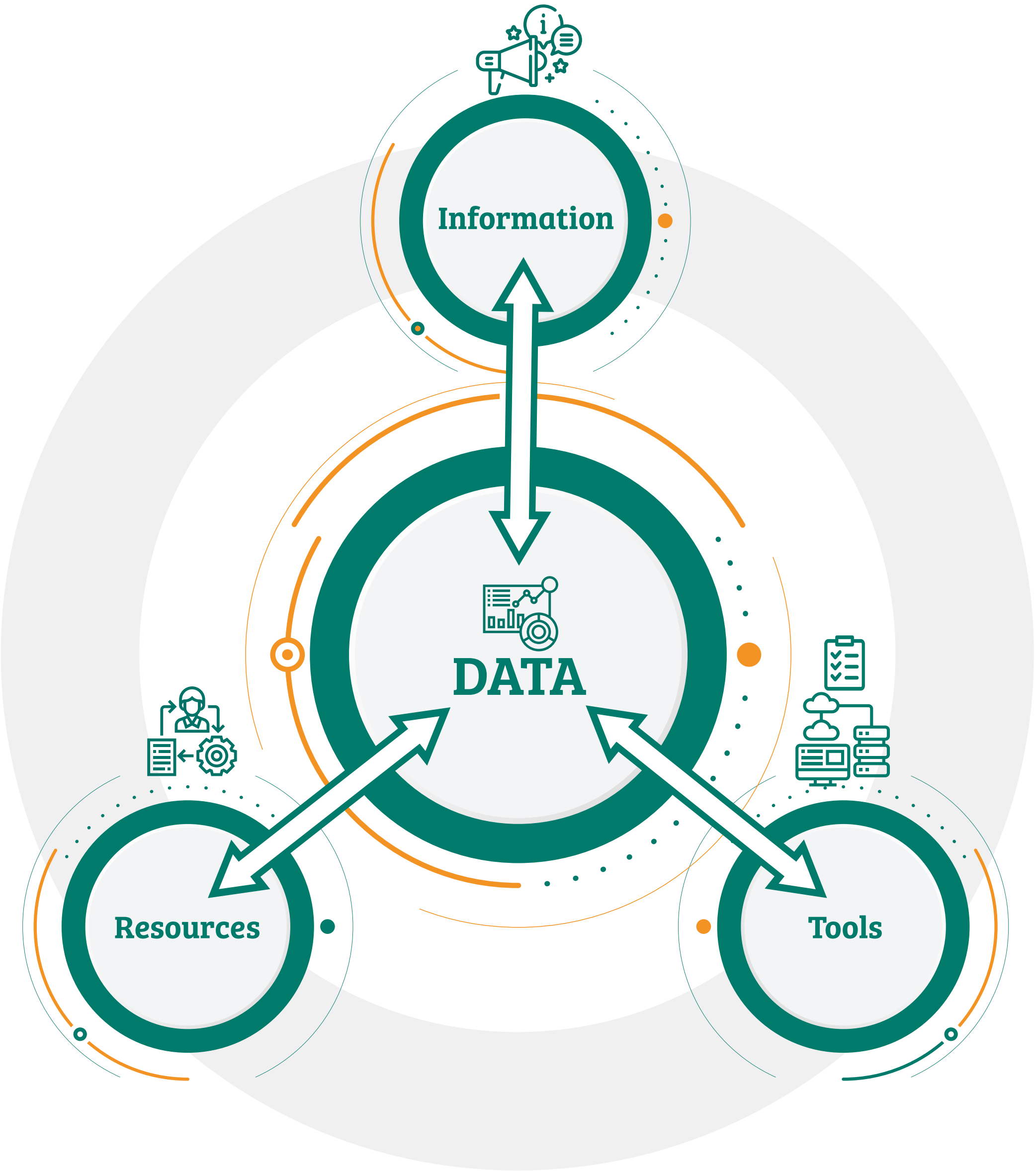


Figure 4: Data, information, resources and tools are all needed.

As we revealed in **Section 4.3**, a lack of data, knowledge and tools featured strongly among the challenges that researchers expressed. “How do I set a baseline for sustainability?”, “how do I compare with alternatives?”, “how can we consolidate our efforts across the organisation?” The themes that came through reflected the kinds of decisions that must be made at both a strategic and operational level, for example:

- choosing between single-use plastic or washing glassware, or
- deciding to invest in new instruments or facilities, or
- making changes in the design of a research project.

A few respondents reported that resources (such as guides and publications) exist, people simply need to look for them. But the majority highlighted resources as a significant knowledge gap.

Researchers suggested multiple communication methods and channels through which information and training could be shared with people:

- **by producing resources in a variety of formats**, for example, manuals, apps, guidelines, databases, supplier datasheets, environmental footprint calculators, prompts (stickers, signage), checklists, how-to guides, case studies, decision trees, professional reference guides, videos, podcasts, webinars
- **by making them accessible**, including online, print, open source, centralised, usable by non-experts, relevant to different contexts, up-to-date opportunities for shared or pro-bono training as well as centralised training in large organisations.

During discussions, our members also raised a number of knowledge areas that training could focus on. Again, these reflected the different levels of expertise – of an individual or laboratory – and where they are on their sustainability journey. These knowledge areas need to be relevant to different contexts, including resource-limited situations and variations in environmental priorities and support. The most common categories suggested were:

- general information about sustainability
- green chemistry, generally, and aspects relevant specifically to different subfields or types of laboratory (for example, synthesis, medicinal chemistry, analytical science)
- waste management for hazardous and non-hazardous chemicals, plastics and consumables, instruments, and equipment. This should include options like: reuse, recycling and incineration; understanding the environmental footprint of those options; what local options are currently available; the most up-to-date information and whether realistic alternatives exist
- baseline calculations for standard, average or typical processes and instruments
- tools that could be used by an individual, laboratory or research programme to enable detailed comparison of their options and suggest alternatives (for example, to a process, reaction, consumable, chemical or equipment). Some suppliers provide tools to allow researchers to compare the 'greenness' of various synthetic routes or chemical processes using the *12 Principles of Green Chemistry*. These tools could also cover financial, research quality and health and safety aspects. Life cycle assessments should also be included in order to consider the upstream, use and downstream impacts of a product or process
- validated sustainability credentials for instruments, equipment and consumables for a range of uses and end-of-life scenarios
- tools to record, share and access relevant sustainability related data (about a particular instrument or process, for example).

Some more specific topics were:

- energy management for air handling, heating and cooling
- carbon costs of computational experiments
- databases of opportunities to recycle or re-home redundant, old or surplus equipment and supplies.

“A simple way to perform a life cycle management analysis. The current methods are too complex and time consuming to be applicable to lab scientists as they make routine decisions in the lab. There are some rules-of-thumb that can be useful - we need more of them and better ways to share the best ones.”

Experienced manager, Industry, United States

5.4 Roles, expertise and collaboration

Many researchers talked about the need for expertise and collaboration in the area of sustainability applied specifically to scientific research.

Some survey respondents (and also in discussions) reported how their university or company makes provision for in-house sustainability expertise.

- **Research sustainability experts** are associated with a laboratory, department or wider research strategy or support function. They develop good practice and advise or work in partnership with colleagues. Examples are formal roles like Sustainability Officer or Research Sustainability Manager.
- **Sustainability is made a formal or informal part of a person's role.** This could, for example, be based on their having taken an interest, initiative or leadership in the area and becoming a 'go-to' person for collegial advice. It is also sometimes incorporated into a technician or postdoc role.
- **Sustainability professionals operate in a central function**, such as waste management, procurement or estates.
- **Researchers in other departments** with expertise in areas like life cycle assessment, techno-economic analysis or public health.
- **Researchers in other science and engineering disciplines** share their knowledge (of chemical engineering or green chemistry, for example).

Key opportunities in this area are:

- **the creation of sustainability expert roles** with associated support and career progression. Support might include policies, or additional staff to enable the coordination and training or dissemination of good practice
- **support and recognition for specialist technical staff** who, in many contexts, play a vital role with regard to laboratory sustainability. They are important in many aspects from understanding the baseline environmental footprint of a laboratory or department to designing, implementing and monitoring sustainability-related interventions. This can include getting data on energy and material use, operating instruments, procurement, stock management and waste handling
- **including sustainability related competencies as essential or desirable in existing roles**
- **mechanisms by which researchers at smaller or resource-limited organisations can access expertise** via:
    - communities, fora and resources
    - sharing costs of access to paid external expertise
    - volunteering and mentorship by experts
- **multidisciplinary collaboration between people** bringing different expertise and spanning different departments, organisations, countries and sectors.

Some respondents suggested there is a useful analogy with health and safety. For a number of companies, their Environment, Health and Safety (EHS) department, is now their Environment, Health, Safety and Sustainability (EHS&S) department.[73] In many countries and organisations there are baseline expectations related to health and safety for all researchers working in a laboratory. Often, there is support from internal or external experts for non-standard or new situations as well as to inform larger or more complex issues and planning.

> **"The multidisciplinary nature of the field makes it more inaccessible to specialists in unrelated areas and harder for research and information to be carried out and disseminated widely as it necessitates collaboration of many different fields (chemistry, toxicology, biology, environmental scientists etc)."**
>
> **Early career chemist, Research Institute, Canada**

5.5 Data and digital technologies

The availability of data to inform sustainability-related decisions poses a challenge for researchers (see Section 4.3). Harnessing data and, more broadly, digital tools and technologies can potentially reduce the consumption and release of chemicals, materials and energy. This is something we explore in more detail in our *Digital Futures* report.

Digital tools can bring cost, health and safety benefits as well as the potential for greater access to data and facilities. Artificial intelligence (AI), computational modelling, sensing, and robotics all offer complementary ways of conducting research. However, it is important to consider the life cycle of computers, devices and the environmental impact of computation.

Many of these opportunities involve collaboration between physical, biological and computational sciences, and engineering, as well as social sciences.

- **The recording and sharing of data to enable sustainability-related decision-making and to optimise research programmes:** this brings in general opportunities and challenges such as data standards and repositories, use of electronic laboratory notebooks (ELNs), data-sharing culture and incentives as well as business models and IP protection. There are specific aspects such as the inclusion of and standards for sustainability-related data and meta-data.
- **Using computation to guide physical laboratory experiments:** using techniques spanning computational modelling and simulation, to mining images, text and data in publications to guide the choice of physical experiments. This can reduce the number of physical experiments and associated environmental and other costs.

- **The automation of experiments or processes:** this ranges from the automation of specific types of benchtop or mid-scale measurement, to the automation of experiments to synthesise and analyse compounds or materials. It can help to minimise the use of energy, chemicals and materials. On a larger scale it offers the option of investment in shared facilities within an organisation or between organisations and regions. Automation has the potential to:
  - increase access to facilities
  - increase the outputs of facilities
  - make more efficient use of them from both an environmental and financial perspective.
- **Monitoring, sensing and measurement:** sensors can be used to enable manual or automated sustainability related interventions. Examples include adjusting flow rates in fume hoods, optimising reaction conditions, and instrument configuration. Monitoring use patterns for energy, materials and costs could be done as part of audits, and to establish environmental and financial baselines and to support changes in culture and practice.
- **Sustainability constrained optimisation and closed (or partially closed) loop research design:** factoring in sustainability criteria and data during the research design stage builds sustainability into some or all of the steps, processes, outputs and target applications. (See Section 4.2 for some caveats on having environmental sustainability as a constraint for some or all parts of a research programme.)

Read more about the use of digital technologies in science R&D in our report, *Digital Futures*.

“More data on sustainable practices could be beneficial for motivating people on what judgements to make when investing their time and money. For example, data on energy consumption of producing disposable plastic equipment vs less durable but reusable glass equipment; or a rough order of importance or effectiveness of various sustainable practices.”

PhD student, Academia, United Kingdom

“[...] Progress in automation. Robotic systems make much more efficient use of fume hoods (and in some cases don't need a hood at all). They typically use lower quantities of chemicals and generate a more complete data set that can get to the desired answer faster.”

Experienced manager, Industry, United States

5.6 Culture, incentives and recognition

A frequently occurring theme throughout many discussions and survey responses was the role of culture, mindset and norms in either supporting or hindering a shift to more sustainable research.

Researchers also talked about the lack of recognition and incentives for people to spend time in ways that will work in favour of more sustainable research. Examples of opportunities for different types of incentives and recognition are:

- roles and professional qualifications or certifications for individuals (see also **Section 5.4**)
- including environmental and wider research sustainability activities in an organisation's hiring and promotion decisions
- certification and other internal or external recognition for laboratories, groups, collaborations, departments, programmes, organisations or suppliers
- including environmental and wider research sustainability activities in institutional research assessment by external funders
- including environmental and wider research sustainability activities as a standard part of researcher CVs, for example in the *Resume for Research and Innovation*.
- grants for training or to develop and implement sustainability initiatives
- mechanisms to share, recognise and reward progress in scaling up or finding 'small tweaks' that make an aspect of research more sustainable. For example, via guides, communities and policy developments. (Some survey respondents commented that this is often not the kind of research breakthrough or discovery typically accepted for publication by scholarly journals)
- mechanisms to share negative results and data, and to recognise and reward those efforts (for example, via conferences and seminars)
- highlight publications that include good examples of environmental impact statements
- prizes to highlight role models, share case studies and celebrate good practice and leadership
- collaborative or competitive activities to incentivise collective action such as community targets or challenges
- financial incentives for research leaders, laboratories or departments undertaking sustainability-related initiatives. These could be associated with cost savings arising from the activity. They could also range from smaller-scale activities within a single laboratory (such as recycling, repairing or reusing equipment or consumables), to larger-scale energy-saving initiatives and agreements to share instruments or facilities.

> “The organisation as a whole needs to buy into the sustainability concept, and only then will the sources of information be relevant.”
>
> **Experienced manager, Industry, United Kingdom**

> “For changing teaching laboratory practicals, there is some inertia. Things stick the same because that is the least work option and everybody is too busy to change it and there is little personal incentive to do so ("greening" a teaching activity won't be in anybody's targets, unlike publications and grants, and there is no reward for it so it won't get done).”
>
> **Mid-career lecturer, Academia, United Kingdom**

5.7 New science, engineering and technology solutions

Researchers highlighted three broad areas where there are opportunities for science research and innovation itself to contribute to enabling more sustainable research.

- **Sustainable chemicals, materials and processes:** this covers solvents, catalysts, reagents and plastics. For example:
    - the substitution of critical or toxic elements
    - minimisation of water use
    - design for bio-degradability or recyclability
    - chemicals and materials made from bio, renewable or locally sourced raw materials
    - catalysts enabling reactions requiring less energy
    - developing new synthetic pathways, reaction protocols and processes that are less energy and resource intensive
    - the optimisation of existing reactions (for example, in organic and solid state inorganic synthesis)
    - separation science to remove toxins or recover metal catalysts
    - analytical methods which run faster with less solvent and use less sample, including miniaturisation to enable micro-scale sample preparation and handling of smaller quantities.

- **Innovation in instrumentation and equipment:** opportunities to improve environmental performance through:
  - – miniaturisation, micro-fluidics
  - – advanced separation techniques
  - – the development of energy-saving standby modes
  - – incorporating adjustable settings, such as variable velocity and temperature, adding sensors to provide data to inform human or automated decisions
  - – higher performance filters for recirculating fume cupboards including for nano-particulates
  - – the development and deployment of batteries for high-power applications
  - – innovating in response to new regulation, environmental standards and customer expectations.
- **The application of life-cycle and socio-techno-economic expertise to science research:** studies, tools and calculations to enable decision makers to evaluate opportunities and trade-offs when designing, supporting and implementing research programmes and facilities.

Advances in these research areas will:

- be most successful if there is collaboration between people in a range of science, engineering and social science areas. This also needs to happen between people working in universities and companies, including instrument manufacturers and suppliers
- have wider applications in developing, deploying and manufacturing sustainable products and processes
- need to be safe, cost-effective and have the same performance in terms of research and product quality.

They may also bring benefits to improvements in health and safety, cost (potentially), as well as opportunities for suppliers.

> **“We try to use less energy but a lot of instruments, e.g. mass spectrometers, need to be permanently on but in a standby state when not being used to make measurements. Work needs to be done by the manufacturers to reduce energy consumption when in this mode.”**

Experienced technician, Academia, United Kingdom

> **“If we want to progress with research we sometimes have to make compromises when thinking about efficiency and quality of result gathering and implementation. It is often a mistake to think that something that appears to be more environmentally friendly will actually be the best long-term solution.”**

Experienced researcher, Academia, Germany

5.8 Regulation, policies and enablers

There are many ways in which different organisations and institutions can support, enable and mandate changes that will result in more sustainable research. These include universities, research institutes and companies, as well as regulators, funders, publishers and governments. Actions could include the following, with significant opportunities for co-development with the research community:

- Mandating sustainable practices and setting targets.
- Simplifying and speeding up routes to certify or licence more sustainable processes and products.
- Introducing restrictions on specific substances or processes.
- Including environmental impact and mitigation in internal and external evaluations of laboratory, department or organisational performance.
- Developing environmental impact standards or expectations and disclosure requirements (for example, as part of funding or publication processes, and with associated support for peer reviewers).
- Embedding sustainability in organisational culture including role-modelling and prioritisation by organisational leaders.
- Including sustainability-related requirements as part of standard operating procedures and risk assessments.
- Clarifying policies regarding equipment sharing, covering procurement, operation, maintenance and upgrades.
- Centralising and pooling resources; share within and between groups, departments and organisations, for example:
    - to explore and make a greater range of waste management options viable than may be possible for an individual laboratory
    - enable access to, and more efficient use of, research instruments and equipment
    - stores and schemes that enable surplus supplies and equipment to be used
- Training, career development and sharing of practice and case studies.

> **“So much of the pharmaceutical industry is driven by speed to aid patients as quickly as possible that it is hard to simultaneously deliver the best product for the environment. Regulatory concerns lead to a reluctance to change once a manufacturing process is improved, so we need to work together to find ways to simplify the ways to change the processes to marketed products. The most environmentally sustainable manufacturing process is usually the least expensive, so it is a win all around.”**

Experienced manager, Industry, United States

"My lab was a little reluctant initially to engage with the My Green Lab's certification, assuming that there would be a lot of demands that could not be done because it would compromise our research work. It turns out that with small changes that have really no impact on the technical work, we could go a long way to saving a lot of energy and becoming more environmentally friendly and sustainable in the longer term."

Early career researcher, Academia, Ireland

5.9 Funding, investment and business models

Many of the solutions suggested in the previous sections require one-off investments, a commitment to recurring costs, or both. There is, however, a significant opportunity for partnership and collaboration to minimise duplication and to accelerate progress in improving the environmental sustainability of research.

Depending on the context there will be different options, requirements and constraints in terms of internal, external and business funding models or cases.

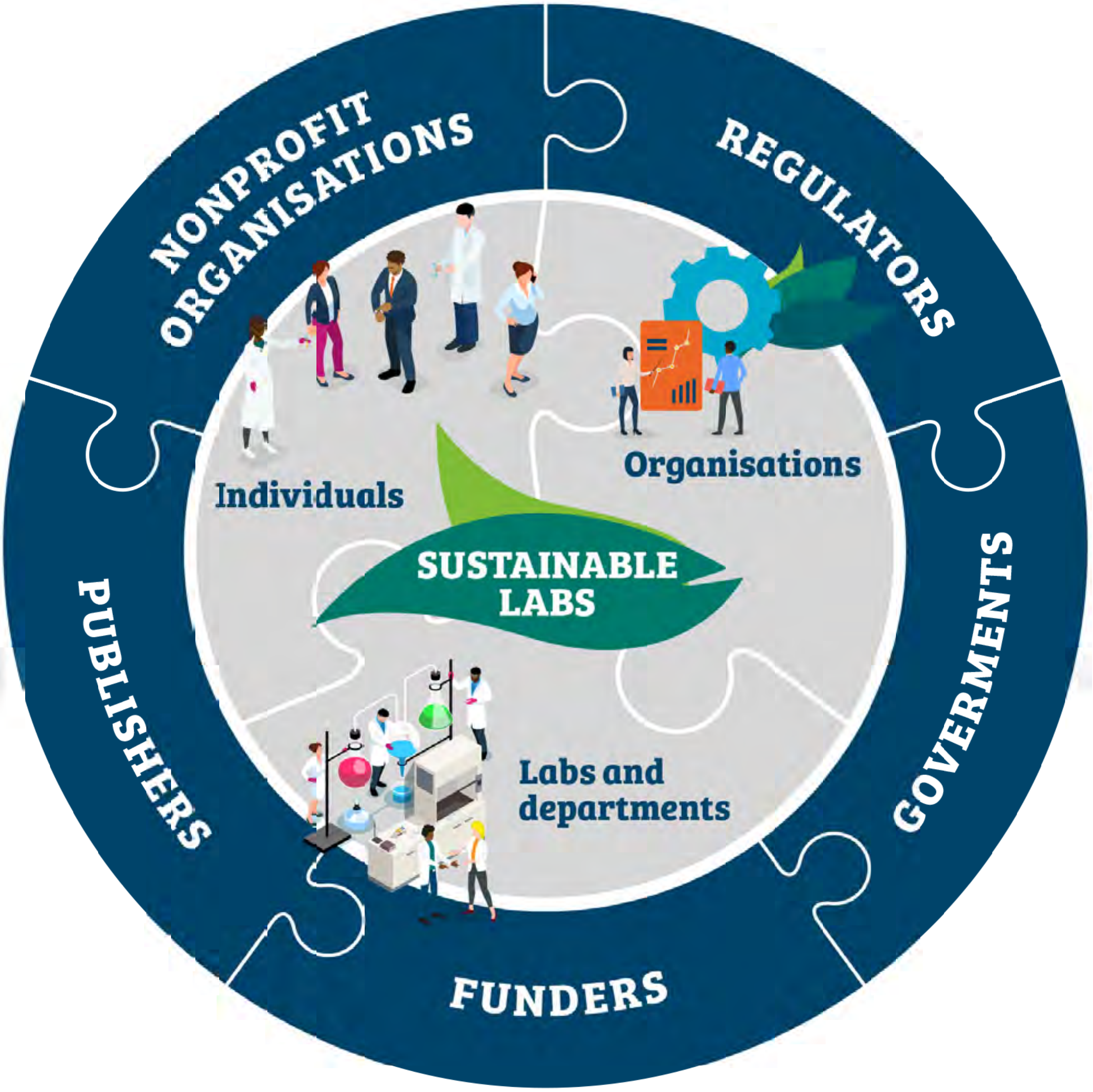
Examples include:

- investment in new and upgraded equipment, buildings or facilities. This could be wide-ranging and include things like specialised scientific instruments and facilities, solar panels, centralised waste management or procurement and storage facilities
- costs associated with hiring in-house or external sustainability professionals as well as the ongoing professional development of specialist technical staff
- funding for audits, baseline calculations, and the development of tools to enable the creation and implementation of sustainability programmes
- costs associated with creating and connecting communities and enabling collaboration
- costs associated with research that will help overcome major technical barriers as well as 'tweaks' that will deliver broad improvements for many research projects
- business models to enable data sharing and the reporting of negative results.

"[..]Funding for research which addresses specific technical aspects even if they're not 'fashionable' i.e. solutions for running reactions at lower temps, improving waste management, etc."

PhD student, Academia, United Kingdom

Figure 5: All of the people, organisations and structures in the research ecosystem have a role in making research more environmentally sustainable.



“We have just started our Green Chemistry journey and intend to be more sustainable and environmentally friendly in the future.”

Experienced manager, Academia, United Kingdom

“Thinking/perception/practices in different places/culture/environments may be different from place to place, the way to reach 'sustainability' may not be the same.”

Experienced researcher, Academia, Thailand

“My group has a generally good culture of taking care of our planet. Incoming group members soon become aware of this and fit in with the ethos.”

Experienced researcher, Academia, Germany

“Environmental sustainability is part of the mission of my research group.”

Experienced researcher, Academia, Belgium

“[...] The real gains are to be made through green chemistry education and a green chemical emphasis on research which translates to greener processes being adopted industrially and as part of a greener wider society[...]”

Early career lecturer, Academia, United Kingdom

“We have a sustainability committee driven by PhD students, they use a variety of sources to think about options.”

Experienced researcher, Academia, Netherlands

Annex: Methodology

This report is based on:

- desk research based on reports, guidelines, resources and peer-reviewed literature
- survey responses from more than 670 people working in chemical sciences research laboratories in 70 countries (the online survey ran between December 2021 and January 2022)
- community views gathered via:
  - discussions by Royal Society of Chemistry Subject Community Councils and their sustainability working groups
  - a survey of the Royal Society of Chemistry's global community
  - advice and initial feedback on the survey from members of the Royal Society of Chemistry Science and Innovation Leadership Forum.

Survey demographics

Table A1: Q1. Where are you based? RSC Sustainable Laboratories Researcher Survey, 2021. (n=671)

Australia	2%
China	8%
Europe (excluding UK)	18%
India	7%
Japan	4%
Nigeria	2%
Other*	13%
Russia	2%
South Korea	2%
United Kingdom	38%
United States	4%

*Other: aggregated data for countries with less than 10 respondents.

Table A2: Q2. What is your occupation? RSC Sustainable Laboratories Researcher Survey, 2021. (n=675)

	% of respondents
Manager	5%
Senior research/practising chemist	7%
Research/practising chemist	8%
Academic – teaching focus	10%
Academic – contract staff with a research focus	11%
Student	16%
Other (e.g. teacher, sustainability professional, retired, not currently employed)	17%
Academic – research focus	26%

Table A3: Q3. What is your sector? RSC Sustainable Laboratories Researcher Survey, 2021. (n=675)

	% of respondents
Academia (including students)	56%
Company with >250 employees	14%
Education	10%
Research Institute	6%
Company with <250 employees	5%
Government	2%
Other (e.g. government, consulting, self-employed)	7%

Table A4: Q4. How would you describe your research field? Select all that apply. RSC Sustainable Laboratories Researcher Survey, 2021. (n=675)

Materials chemistry	38%
Analytical chemistry	27%
Organic chemistry	25%
Inorganic chemistry	18%
Synthetic chemistry	17%
Green chemistry	17%
Physical chemistry	17%
Environmental chemistry	14%
Other	12%
Chemical biology	11%
Medicinal chemistry	11%
Chemical engineering	11%
Computational chemistry	8%
Chemical industry	8%
Theoretical chemistry	2%

For 'other', respondents indicated their research fields as:

- chemistry education
- biology e.g. molecular biology, biotechnology
- catalysis
- nuclear/radio chemistry
- instrument development.

Table A5: Q5. What is your career stage? RSC Sustainable Laboratories Researcher Survey, 2021. (n=675)

Experienced	31%
Early career	23%
Mid-career	21%
PhD student	17%
Undergraduate or taught postgraduate student	5%
Retired	3%

73% selected ‘yes’ in response to Question 6: ‘Does your job role involve running a research group and/or supervising or overseeing the work of others, e.g. designing research projects, managing staff? (Note that this could include, for example, postdoctoral researchers who are overseeing the work of PhD researchers.)

61% indicated they are RSC members (Question 7).

Survey questions and results

This section contains some more detailed data not covered in the main body of the report.

Figure A1: Q8. To what extent do you agree or disagree with the following statements. RSC Sustainable Laboratories Researcher Survey, 2021. (n=620)

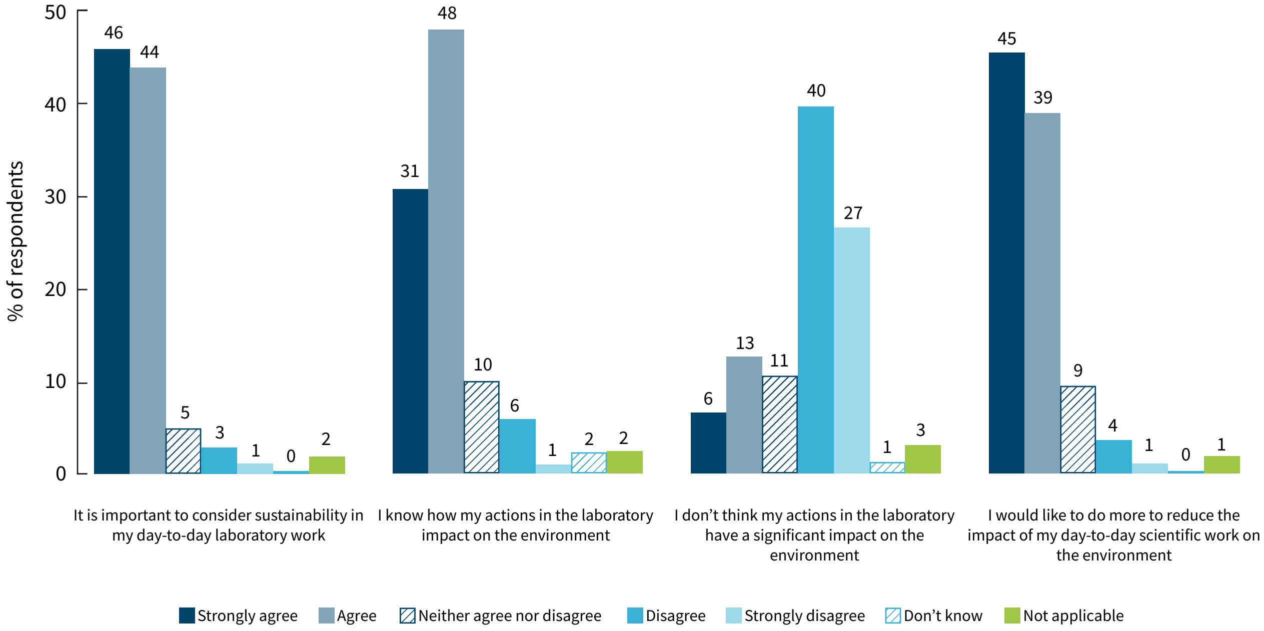


Figure A2: Q9. As a scientist, where do you think your actions can make a difference to environmental sustainability? Tick all that apply. RSC Sustainable Laboratories Researcher Survey, 2021. (n=619)

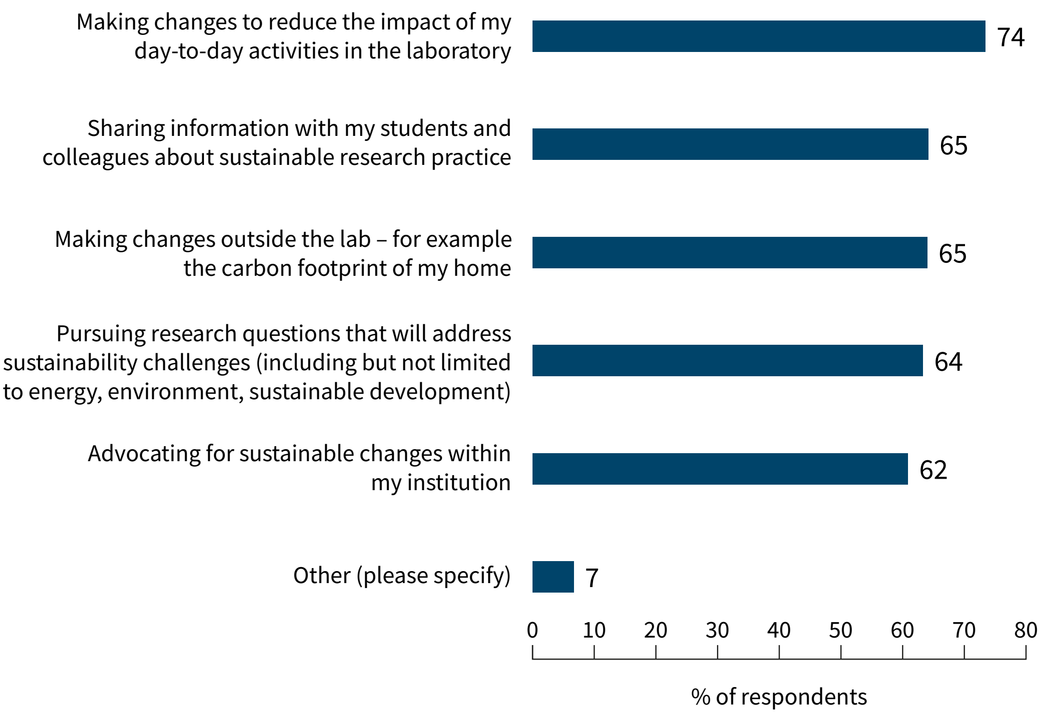


Figure A3: Q10. In the last two years, have you made any changes to your own research activities, or those of your research group, team or department, in order to reduce the environmental impact of your work? RSC Sustainable Laboratories Researcher Survey, 2021. (n=620)

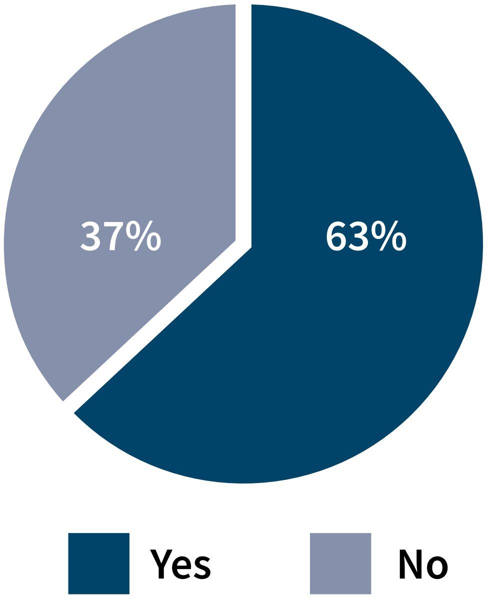
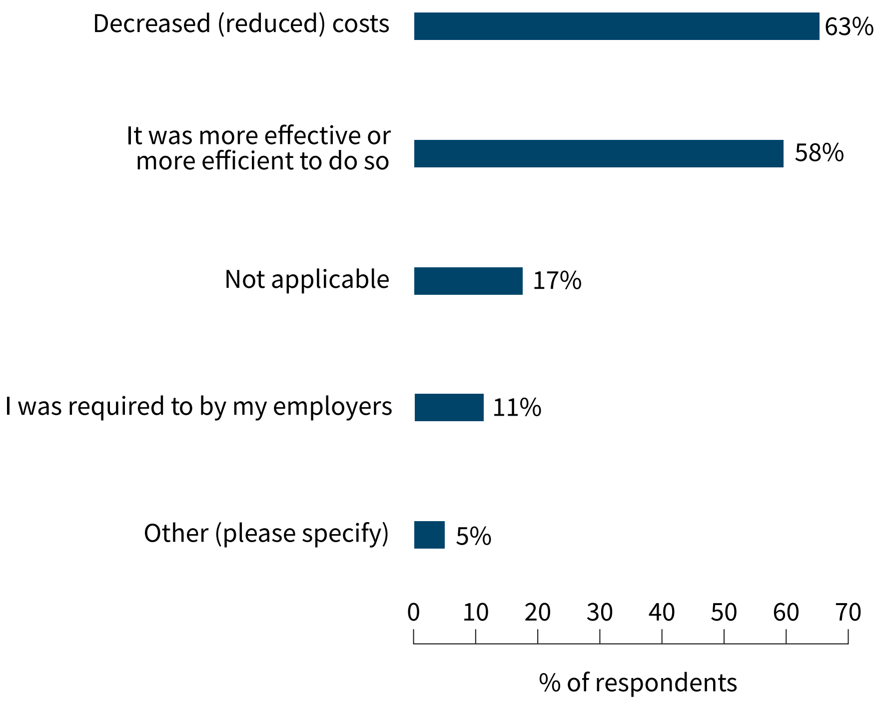


Figure A4: Q13. Were you motivated to take any of the previous measures for reasons other than environmental sustainability? RSC Sustainable Laboratories Researcher Survey, 2021. (n=601)



Free-text questions and additional questions not listed in Annex or body of the report:

Q14 Do you take any other actions in the lab to increase the sustainability of your day-to-day work [in addition to Q12 and Q13]? Please comment:

Q16 Do you face any other barriers not covered by the options above [in Q15]?

Q17 Where do you go to access information about sustainability in the laboratory? Click all that apply.

Q18 Please share details of any resources that you have found particularly useful

Q19 Do you have access to formal training or induction on sustainability principles in research work?

Q20 What are the technical areas where you feel most in need of guidance? For example, green chemistry, general lab sustainability principles, energy consumption of equipment or processes, waste management and recycling

Q21 What type of resources would be most useful to you in developing your knowledge and ability to implement sustainable practices in your scientific work? E.g. training, online resources, events, access to expertise, networks, funding, etc

Q22 What are the biggest technical barriers to more sustainable research practices in science and engineering?

Q23 Where can chemistry itself play a role in addressing these barriers?

Q24 Thinking about sustainability within research or laboratory practice, is there anything else you would like to add?

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References

1 UK Higher Education Estates Management environmental information for 2020/21 is available at https://www.hesa.ac.uk/news/09-08-2022/estates-environmental-information-202021

2 Bull, J. W., Taylor, I., Biggs, E., Grub, H. M. J., Yearley, T., Waters, H. & Milner-Gulland, E. J., 'Analysis: the biodiversity footprint of the University of Oxford', *Nature*, April 2022 https://www.nature.com/articles/d41586-022-01034-1

3 World Resources Institute and World Business Council for Sustainable Development, *Greenhouse Gas Protocol, Corporate Value Chain (Scope 3) Accounting and Reporting Standard*, 2011 https://ghgprotocol.org/sites/default/files/standards/Corporate-Value-Chain-Accounting-Reporing-Standard_041613_2.pdf

4 National Renewable Energy Laboratory (NREL), *Laboratories for the 21st Century: An Introduction to Low-Energy Design*, 2008 https://www.nrel.gov/docs/fy08osti/29413.pdf

5 Energy Star Portfolio Manager, Technical Reference, *US Energy Use Intensity by Property Type*, 2021 https://portfoliomanager.energystar.gov/pdf/reference/US%20National%20Median%20Table.pdf

6 Hawkins, D., Hong, S. M., Raslan, R., Mumovic, D., and Hanna, S., 'Determinants of energy use in UK higher education buildings using statistical and artificial neural network methods', *International Journal of Sustainable Built Environment*, 2012, 1(1), 50–63, http://dx.doi.org/10.1016/j.ijsbe.2012.05.002

7 University of Oxford, *Environmental Sustainability Strategy*, 2018, https://sustainability.admin.ox.ac.uk/files/environmentalsustainabilitystrategy.pdf

8 The University of Cambridge, The Cambridge Green Challenge, *Green Labs – Frequently Asked Questions*, 2019, https://www.environment.admin.cam.ac.uk/greenlabs_faqs

9 Hogue, C. 'Energy-guzzling fume hoods put on a diet', *Chemical and Engineering News*, 2022 https://cen.acs.org/environment/sustainability/Energy-guzzling-fume-hoods-put-diet/100/i8

10 May, M. J., 'Adding efficiency to general lab equipment', *Science*, 2016, 352, 614–616 https://www.science.org/content/article/adding-efficiency-general-lab-equipment

11 My Green Lab, 'Energy', https://www.mygreenlab.org/energy.html

12 Arnott, A., Evans, A., Farley, M., and McTeir, B., 'Efficient ULT freezer storage', The University of Edinburgh, 2015, https://www.ed.ac.uk/files/atoms/files/efficient_ult_freezer_storage.pdf

13 Council for the Central Laboratory of the Research Councils, *ISIS Annual Report 2005 – Review of the year*, https://www.isis.stfc.ac.uk/Pages/annual-review-2005.pdf

14 CERN, *CERN Environment Report 2019–2020*, https://hse.cern/environment-report-2019-2020

15 CERN, 'Emissions', *CERN Environment Report 2019–2020*, https://hse.cern/environment-report-2019-2020/emissions

16 UKRI Science and Technology Facilities Council, *ISIS Neutron and Muon Source: Annual Review 2021*, https://www.isis.stfc.ac.uk/SiteAssets/Pages/ISIS-2021-Annual-Review-out-now/ISIS%20Annual%20Review%202021.pdf

17 The University of Strathclyde, *Sustainable Laboratory Good Practice Guide*, 2021, https://www.strath.ac.uk/professionalservices/media/ps/estatesmanagement/sustainability/sustdocuments/S-Labs-Good_Practice_Guide.pdf

18 'HE Provider Data: Estates Management', 2022, Higher Education Statistics Agency, https://www.hesa.ac.uk/data-and-analysis/estates/environmental

19 Kerton, F., and Marriott, R., *Alternative Solvents for Green Chemistry: Edition 2*, RSC Publishing, 2013, https://pubs.rsc.org/en/content/ebook/978-1-84973-595-7

20 Abou-Shehadad, S., Dunne, P. J. Hayler, J., McElroy, R. C., Prat, D., Sneddon, H., and Wells, A., 'CHEM21 selection guide of classical- and less classical-solvents', *Green Chemistry*, 2015, https://pubs.rsc.org/en/content/articlelanding/2016/gc/c5gc01008j

21 'Reagent Guides', *ACS Green Chemistry Institute*, https://reagents.acsgcipr.org/reagent-guides

22 Andraos, J., 'Useful Tools for the Next Quarter Century of Green Chemistry Practice: A Dictionary of Terms and a Data Set of Parameters for High Value Industrial Commodity Chemicals', *ACS Sustainable Chemical Engineering*, 2018, https://pubs.acs.org/doi/full/10.1021/acssuschemeng.7b03360

23 Clark, J. H., Constantinou, A., Jones, L. C., McElroy, R. C., Summerton, L., 'Towards a holistic approach to metrics for the 21st century pharmaceutical industry', *Green Chemistry*, RSC Publishing, 2015, https://pubs.rsc.org/en/content/articlelanding/2015/GC/C5GC00340G

24 Urbina, M., Reardon, E. E., and Watts, A. J. R., 'Labs should cut plastic waste too', *Nature*, 2015, 528, 479, https://www.nature.com/articles/528479c

25 Microbiology Society, ‘Does science have a plastic problem? Microbiologists take steps to reducing plastic waste’, *ScienceDaily*, 2020, https://www.sciencedaily.com/releases/2020/10/201015003437.htm

26 Bemis, J., ‘Plastic to Glassware Conversions at HSCRB Saves Money, Reduces Waste’, Harvard University, 2011, https://green.harvard.edu/news/plastic-glassware-conversions-hscrb-saves-money-reduces-waste

27 ‘Plastic pledge’, University of Leeds, https://sustainability.leeds.ac.uk/plastic-pledge

28 University College London, ‘UCL divests from fossil fuels as it launches bold new sustainability strategy’, 2019, https://www.ucl.ac.uk/news/2019/oct/ucl-divests-fossil-fuels-it-launches-bold-new-sustainability-strategy

29 United Nations Environmental Programme, *Addressing Single-Use Plastic Products Pollution using a Life Cycle Approach*, 2021, https://www.unep.org/resources/publication/addressing-single-use-plastic-products-pollution-using-life-cycle-approach

30 Farley, M., and Nicolet, B. P., ‘Re-use of labware reduces CO_2 equivalent footprint and running costs in laboratories’, *Biology*, 2022, https://www.biorxiv.org/content/10.1101/2022.01.14.476337v1

31 See for example Critical Raw Materials, European Commission, https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en and the United States Geological Survey 2022 List of Critical Materials https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals

32 See for example 'The Criticality of Metals', Yale School of the Environment Center for Industrial Ecology, https://cie.research.yale.edu/research/criticality-metals

33 See for example Bamana, G., Dunn, J. B., Miller, J. D., Young, S. L., ‘Addressing the social life cycle inventory analysis data gap: Insights from a case study of cobalt mining in the Democratic Republic of the Congo’, *One Earth*, 2021, 4 (12), 1704–1714, https://doi.org/10.1016/j.oneear.2021.11.007

34 ‘The Working Group on Transforming the Extractive Industries for Sustainable Development’, *United Nations Environment Programme*, https://www.unep.org/events/working-group/transforming-extractive-industries-sustainable-development

35 For example, the UK Biotechnology and Biological Sciences Research Council found in a 2019 *Review of Data-Intensive Bioscience* that at least 50% of research grants now involve large-scale biological data and can be considered ‘data-rich’. https://www.ukri.org/wp-content/uploads/2020/11/BBSRC-201120-ReviewOfDataIntensiveBioscience.pdf

36 ‘Digital Futures’, the Royal Society of Chemistry, 2019, https://www.rsc.org/new-perspectives/discovery/digital-futures

37 For a discussion of the impacts of scientific hardware and computing, and possible mitigations, see Farley, M., Jeffery, K. J, Rae, C. L., and Urai, A. E., ‘Climate crisis and ecological emergency: Why they concern (neuro) scientists, and what we can do’, *Brain Neurosci Adv*, 2022, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8891852/#bibr33-23982128221075430

38 Strathclyde, *Laboratory Good Practice*, https://www.strath.ac.uk/professionalservices/media/ps/estatesmanagement/sustainability/sustdocuments/S-Labs-Good_Practice_Guide.pdf

39 Mills, E., Sartor, D., 'Energy use and savings potential for laboratory fume hoods', *Energy*, 2005, 30, 1859–1864 https://www.sciencedirect.com/science/article/abs/pii/S0360544204004906

40 ‘Increase ULT freezer temperature to -70 °C and save energy’, University of Exeter, https://www.exeter.ac.uk/about/sustainability/sustainablelabs/energy/ultfreezers

41 ‘Decision for Typical Domestic Consumption Values 2020’, UK Office of Gas and Electricity Markets (ofgem) https://www.ofgem.gov.uk/publications/decision-typical-domestic-consumption-values-2020

42 Strathclyde, *Laboratory Good Practice*, https://www.strath.ac.uk/professionalservices/media/ps/estatesmanagement/sustainability/sustdocuments/S-Labs-Good_Practice_Guide.pdf

43 ALLEA, *Towards Climate Sustainability of the Academic System in Europe and beyond*, 2022, https://allea.org/wp-content/uploads/2022/05/ALLEA-Report-Towards-Climate-Sustainability-of-the-Academic-System.pdf

44 Hao, K., ‘Training a single AI model can emit as much carbon as five cars in their lifetimes’, *MIT Technology Review*, 2019, https://www.technologyreview.com/2019/06/06/239031/training-a-single-ai-model-can-emit-as-much-carbon-as-five-cars-in-their-lifetimes

45 ‘Water Conservation’, Stanford University, https://sustainable.stanford.edu/cardinal-green/cardinal-green-labs/water-conservation

46 ‘Water’, My Green Lab, https://www.mygreenlab.org/water.html

47 ‘Net Zero Tracker’, https://zerotracker.net

48 My Green Lab, *The Carbon Impact of Biotech & Pharma – A roadmap to 1.5 °C*, 2021, https://www.mygreenlab.org/uploads/2/1/9/4/21945752/the_carbon_impact_of_biotech___pharma-_final.pdf

49 Science Based Targets, https://sciencebasedtargets.org

50 ‘Ambition Zero Carbon’, AstraZeneca, https://www.astrazeneca.com/sustainability/environmental-protection/ambition-zero-carbon.html

51 ‘How R&D is helping drive a greener future’, AstraZeneca, https://www.astrazeneca.com/what-science-can-do/topics/sustainability/how-rd-is-helping-drive-a-greener-future.html#

52 ‘Environmental sustainability’, GSK, https://www.gsk.com/en-gb/responsibility/environmental-sustainability

53 Unilever, *Climate Transition Action Plan*, 2021, https://assets.unilever.com/files/92ui5egz/production/bbe89d14aa9e0121dd3a2b9721bbfd3bef57b8d3.pdf/unilever-climate-transition-action-plan-19032021.pdf

54 ALLEA, *Towards Climate Sustainability*, https://allea.org/wp-content/uploads/2022/05/ALLEA-Report-Towards-Climate-Sustainability-of-the-Academic-System.pdf

55 Universities UK*, Confronting the climate emergency – A commitment from UK universities*, 2021, https://www.universitiesuk.ac.uk/sites/default/files/field/downloads/2021-10/confronting-the-climate-emergency.pdf

56 ‘Environmental sustainability’, UK Research and Innovation, https://www.ukri.org/about-us/policies-standards-and-data/environmental-sustainability

57 NREL, *Laboratories for the 21st Century*, https://www.nrel.gov/docs/fy08osti/29413.pdf

58 ‘AstraZeneca unveils The Discovery Centre (DISC) in Cambridge’, AstraZeneca, 2021, https://www.astrazeneca.com/media-centre/press-releases/2021/astrazeneca-unveils-the-discovery-centre-disc-in-cambridge.html

59 Green Building Design, *Bristol Myers Squibb*, https://www.bms.com/about-us/sustainability/environment/green-building-design.html

60 ‘The Carbon Neutral Laboratory’, *University of Nottingham*, https://www.nottingham.ac.uk/chemistry/research/centre-for-sustainable-chemistry/the-carbon-neutral-laboratory.aspx

61 Tighe, E., ‘Science and Engineering Complex named one of the world’s healthiest lab buildings’, *The Harvard Gazette*, 2021, https://news.harvard.edu/gazette/story/2021/03/new-complex-recognized-as-one-of-the-worlds-healthiest-lab-buildings

62 A very small selection of university programmes is: Oxford University, https://sustainability.admin.ox.ac.uk/labs; Cambridge University, https://www.environment.admin.cam.ac.uk/green-labs; Edinburgh University, https://www.ed.ac.uk/sustainability/programmes-and-projects/sustainabilityinnovation-leadership/reducing-carbon-and-waste/laboratories; University of Bristol, https://www.bristol.ac.uk/sustainability/get-involved/green-labs

63 See for example the *Science Horizons* report, Royal Society of Chemistry, 2018, https://www.rsc.org/new-perspectives/discovery/science-horizons

64 ‘NIH Green Labs Program', National Institutes of Health, https://nems.nih.gov/green-teams/Pages/NIH-Green-Labs-Program.aspx

65 ‘MSCA Green Charter’, European Commission, https://marie-sklodowska-curie-actions.ec.europa.eu/about-msca/msca-green-charter

66 ‘Carbon offset policy for travel’, Wellcome, https://wellcome.org/grant-funding/guidance/carbon-offset-policy-travel

67 Cancer Research UK, *Position Statement on Environmental Sustainability of Research*, 2022, https://www.cancerresearchuk.org/sites/default/files/cancer_research_uk_position_statement_on_environmental_sustainability_of_research_2022_1.pdf

68 Finkbeiner, M., and Reich, Y., ‘The research environmental impact disclosure’, *Research in Engineering Design*, 2021, 33, https://link.springer.com/article/10.1007/s00163-021-00379-4

69 An example is concern over inclusion of the ‘do no significant harm’ principle in Horizon Europe: https://sciencebusiness.net/news/meps-decry-inclusion-do-no-significant-harm-principle-horizon-europe

70 Arnott, A., Bennet, M., Farley, M., Lewis, A., Smith, D., ‘Sustainable Laboratory Equipment Metering, Procurement, and Operations Guide’, University College London, https://www.ucl.ac.uk/sustainable/sites/sustainable/files/sustainable_lab_equipment_guide_-_metering_purchasing_operations.pdf

71 For pharmaceuticals some examples of pharmacopoeias globally include the International Pharmacopoeia, The European Pharmacopoeia, The United States Pharmacopeia and The British Pharmacopoeia.

72 This is consistent with views we have heard in our Green Shoots, Digital Futures and Science Horizons work which have pointed to the inclusion of sustainability and digital skills as part of science education and professional development.

73 The National Association for Environmental Health, Safety and Sustainability https://www.naem.org/about/ehs

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