Master Thesis

Environmental Sustainability in Biobanking
Opportunities to reduce environmental impact of manual Ultra-Low Temperature (ULT) sample storage

Submitted by

Anita Litschauer

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Univ.-Prof. Dr.rer.nat. Berthold Huppertz

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Statutory Declaration

I declare on my honor that I have written this dissertation independently and without assistance, that no sources other than those cited were used and that the sources used verbatim or in substance have been marked as such.

Graz, 10th June 2020 *Anita Litschauer*

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Abstract (German)

Um zur Verringerung des ökologischen Fußabdrucks im Gesundheitswesen beizutragen, wurden eine Reihe von Umweltinitiativen gestartet, darunter auch Initiativen im Bereich der Laborpraxis. Biobanken mit ihren Aktivitäten, welche die Sammlung, Konservierung, Verarbeitung, Lagerung und Verteilung von Proben und den dazugehörigen Daten umfassen, haben kürzlich auf dem Gebiet der Nachhaltigkeit von Laboratorien Aufmerksamkeit erregt. Um qualitativ hochwertige, für den künftigen Verwendungszweck geeignete Proben in Biobanken zu gewährleisten, sind robuste Lagerungsbedingungen von entscheidender Bedeutung. Dabei sind für die Langzeitlagerung von Proben in Biobanken ultratiefe Lagertemperaturen, die in so genannten Ultratiefkühlschränken erreicht werden, üblich. Ultratiefkühlschränke sind bekanntermaßen einer der energieintensivsten Geräte in Laboratorien, während Biobanken mit großen Probensammlungen Hunderte von Ultratiefkühlschränken in ihren Einrichtungen betreiben können.

Ziel dieser Arbeit war es, Möglichkeiten zur Verringerung des ökologischen Fußabdrucks der manuellen Lagerung von Proben bei ultratiefen Temperaturen in Biobanken zu identifizieren, mit dem übergeordneten Ziel, dass Biobanken Praktiken in Betracht ziehen, die weiter zu den Zielen der nachhaltigen Entwicklung beitragen, und das Thema ‚Ökologische Nachhaltigkeit im Biobanking' hervorzuheben.

Um Möglichkeiten zur Erfüllung der Umweltverantwortung im Zusammenhang mit der Lagerung von Proben und Ultratiefkühlschränken zu identifizieren, welche in der universitären wissenschaftlichen Forschung beworben und praktiziert werden, wurden universitätsbasierte Nachhaltigkeitsprogramme (Green Lab Programme) zur Evaluierung ausgewählt. Die in diesen Programmen identifizierten Aktionen wurden mit den Aktionen im Zusammenhang mit der Lagerung von Proben bei ultratiefen Temperaturen, wie sie in den neuesten verfügbaren ISBER-Best-Practices zu finden sind, verglichen.

Basierend auf der Analyse von 24 internationalen universitätsbasierten Nachhaltigkeitsprogrammen wurden 31 Aktionen in Form von Maßnahmen, Empfehlungen und Überlegungen zu einer nachhaltigeren Lagerung von Proben bei ultratiefen Temperaturen innerhalb der Themenbereiche Probenmanagement, Management und Wartung der Ultratiefkühlschränke und Beschaffungsüberlegungen identifiziert. Der Vergleich mit den ISBER Best Practices zeigte, dass die verwandten Themenbereiche von

zwei Dritteln der in universitätsbasierten Nachhaltigkeitsprogrammen gefundenen Aktionen in den ISBER Best Practices erwähnt wurden, wenn auch teilweise in einem anderen Kontext.

Die Aktivitäten von Biobanken sind entscheidend für den Fortschritt in der biomedizinischen Forschung und tragen letztlich zu einer besseren Gesundheitsversorgung bei und spielen daher eine wichtige und verantwortungsvolle Rolle für unsere Gesellschaft. Die Umsetzung der ökologischen Nachhaltigkeit in ihren Tätigkeiten würde weiter zu den Zielen der nachhaltigen Entwicklung beitragen. Am Beispiel der Lagerung von Proben bei ultratiefen Temperaturen wird gezeigt, dass es Raum für Verbesserungen durch die Umsetzung einer Reihe von nachhaltigen Praktiken und Überlegungen gibt.

Abstract (English)

A number of environmental initiatives have been started to contribute to the reduction of the environmental footprint in the healthcare sector, including initiatives in the field of laboratory practices. Biobanks with their main activities including the collection, preservation, processing, storage and distribution of samples and related data have recently attracted attention in the field of laboratory sustainability. Robust storage conditions are crucial to ensure high-quality and 'fit for purpose' samples in biobanking and therefore ultra-low storage temperatures, achieved in so-called ultra-low temperature (ULT) freezers, are common for long-term storage in biobanking. ULT freezers are known to be one of the most energy intensive equipment in laboratories, while biobanks, holding large sample collections, may operate hundreds of ULT freezers in their facilities.

The aim of this thesis was to identify opportunities to reduce the environmental impact of manual ultra-low temperature (ULT) storage of samples in biobanks, with the overall aim for biobanks to consider practices contributing to the Sustainable Development Goals and to emphasize the topic 'Environmental Sustainability in Biobanking'.

University-based sustainability programs (Green Lab Programs) were selected for evaluation to identify actions to meet environmental responsibility related to sample storage and ULT freezers promoted and practiced in university-based scientific research. The actions identified in these programs were compared to the actions related to storage of samples at ultra-low temperatures as mentioned in the latest available ISBER Best Practices.

Based on the analysis of 24 international university-based sustainability programs, 31 actions in form of measures, recommendations and considerations towards more sustainable storage of samples at ultra-low temperatures were identified within the topics of sample management, freezer management, freezer maintenance and procurement considerations. The comparison to ISBER Best Practices showed that the related subject areas of two-thirds of actions found in university-based sustainability programs were mentioned in ISBER Best Practices, although partly in a different context.

The activities of biobanks are crucial for the progress in biomedical research and ultimately contribute to better health care and therefore play an important and responsible role for our society. The implementation of environmental sustainability in their operations would

further contribute to the goals of sustainable development. On the example of ultra-low temperature sample storage, it is shown that there is room for improvement through the implementation of a number of sustainable practices and considerations.

Table of Contents

Abbreviations

AUS	Australia
ANSI	American National Standards Institute
BBMRI-ERIC	Biobanking and Biomolecular Resources Research Infrastructure – European Research Infrastructure Consortium
BRC	Biological resource centres
CO_2	Carbon dioxide
CDC	Centers for Disease Control and Prevention
CTRNet	Canadian Tumour Repository Network
CEN/TS	European Committee for Standardization/Technical Specifications
CAN	Canada
CSR	Corporate Social Responsibility
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen
DNA	Deoxyribonucleic acid
EU	European Union
ESBB	European, Middle Eastern & African Society for Biopreservation and Biobanking
EMS	Environmental Management System
FFPE	Formalin-fixed paraffin-embedded
GWP	Global warming potential
HCWH	Health Care Without Harm
HVAC	Heating, ventilation and air conditioning
HIV	Human immunodeficiency virus
HFCs	Hydrofluorocarbons
I^2SL	International Institute for Sustainable Laboratories
ISBER	International Society for Biological and Environmental Repositories
IARC	International Agency for Research on Cancer
ISO	International Organization for Standardization

kWh	Kilowatt hour
LEAF	Laboratory Efficiency Assessment Framework
LEED	Leadership in Energy and Environmental Design
LEDs	Light-emitting diodes
LN_2	Liquid nitrogen
MDGs	Millenium Development Goals
NCI	National Cancer Institute
OECD	Organisation for Economic Cooperation and Development
QM	Quality Management
QMS	Quality Management System
QA	Quality Assurance
QC	Quality Control
R&D	Research & Development
RNA	Ribonucleic acid
RTSS	Room temperature sample storage
SDGs	Sustainable Development Goals
SDSN	Sustainable Development Solutions Network
SLAS	Society for Laboratory Automation and Screening
UNCED	United Nations Conference on Environment and Development
ULT freezer	Ultra-low temperature freezer
USA	United States of America
UK	United Kingdom
UKCRC	UK Clinical Research Collaboration
UCL	University College London
UNESCO	United Nations Educational, Scientific and Cultural Organization
WHO	World Health Organisation

List of figures

List of tables

1 Introduction

1.1 Definition of sustainability and sustainability in general

Sustainability is omnipresent and confronts us today on many levels of our lives. Literally, sustainability implies the capability to support, withstand or endure (1). This characteristic can be assigned to both a goal and a process. Today, many different variants to use the term sustainability can be found. The many different variants to use the term sustainability include: social sustainability, environmental sustainability, sustainable development, sustainable production, sustainable cities and sustainable transport. Sustainability was declared as a common political goal after ecological and social equality became more and more important in our world (1).

There are many different ideas on what sustainability means and how it can be achieved. At the same time, there is no universally agreed definition. However, the most common definition, which also became common language at the United Nations Conference on Environment and Development (UNCED) in 1992, also known as the Rio+20 Conference (2), comes from the Brundtland Report entitled 'Our Common Future', published in 1987 by the United Nations World Commission on Environment and Development (3).

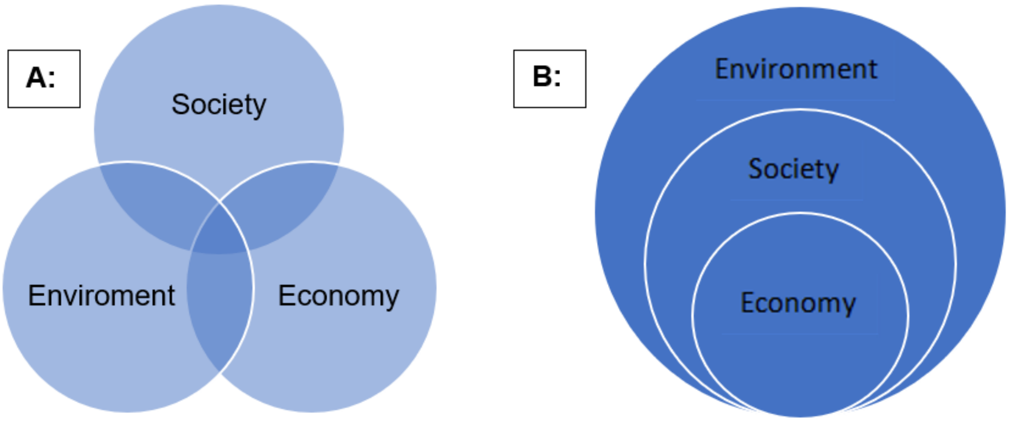
"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (3)

The non-profit corporation Thwink.org (4) defines sustainability in a different way:

"Sustainability is the ability to continue a defined behavior indefinitely." (4)

Three main dimensions are associated with the concept of sustainability, known as the 'three pillars' of sustainability: economic, environmental, and social (4,5). The meaning of economic sustainability is usually that a society should not live economically beyond its means, as this would certainly lead to losses for future generations. In general, an economic system is considered sustainable if it can be operated in the long term. Environmental sustainability is most closely aligned with the idea of not overexploiting nature. Environmentally sustainable would be a way of life that only uses up the natural resources to the extent that they regenerate. Social sustainability is associated with the idea that a state

or a society should be organized in a way that social tensions are kept within limits and conflicts do not escalate, but can be dealt with peacefully and civilly (5).
The concept of sustainability with its three dimensions is described in two different ways, most often the three-pillar model is graphically represented in a Venn diagram in which economic, environmental and social sustainability are equally important, or as three nested concentric circles, with the dimension of economic sustainability in the middle, the three dimensions being interdependent (Figure 1.1).



A: The diagram shows the relationship between the three pillars of sustainability where all three dimensions are equally important.

B: The diagram shows the relationship between the three pillars of sustainability, in which both the economy and society are limited by environmental constraints.

Figure 1.1 Different models of sustainability, adapted from (5)

Although the three pillar model is criticized that it is difficult to operationalize and that it is challenging to derive practical consequences from, it is the most leading framework when thinking about sustainability questions (5,6). More recently, in accordance with the United Nations, UNESCO and Agenda 21, four dimensions of sustainability have been distinguished in the approach called 'Circles of Sustainability', including economic, environmental, political and cultural sustainability (6,7).

1.2 Sustainable Development Goals and health care´s climate footprint

With a massive global effort and action from millions of people working on achieving the Millenium Development Goals (MDGs) from 2000 to 2015, the number of people living in poverty was reduced by more than half compared to the level of 1990, and 1.9 billion people got access to drinking water (8). The fight against diseases such as AIDS, malaria and tuberculosis has been tremendously improved with targeted investments in prevention, diagnosis and treatment, saving an estimated 45 million lives between 2000 and 2015. Regardless of the enormous progress that has been made for many of the Millenium Development Goals (MDGs), inequalities persist and leave substantial gaps. Global carbon dioxide emissions rose between 1990 and 2015 by more than half, and water scarcity already affected 40% of the world's population by 2015. Therefore, as successors to the MDGs, a long-term sustainability agenda was called for by the world's heads of state and government (8).

In September 2015, the United Nations agreed on the Agenda 2030 for sustainable development under the title 'Transforming our world'(9). This ambitious vision was adopted by the 193 member states of the United Nations to address the many challenges of our time. The Agenda 2030 covers the five topics: people, planet earth, prosperity, peace, and partnership. The vision and goal is to create a world which ensures a secure supply of food, water, health and other basic needs for all people, a world in which consumption and production are sustainable and fair and in which all people can live in harmony with fellow human beings and the environment (9).

The Sustainable Development Goals (SDGs) of the Agenda 2030 are a plan for action and represent a target system for decision-making processes at global, national and regional levels (Figure 1.2). The 17 sustainable development goals (SDGs) are listed in Figure 1.3 and are further differentiated into 169 subgoals (10).

Figure 1.2 The Sustainable Development Goals (SDGs), figure taken from (10)
(Source: United Nations, Available from: https://sustainabledevelopment.un.org/)

SDG 1	End poverty in all its forms everywhere
SDG 2	End hunger, achieve food security and improved nutrition and promote sustainable agriculture
SDG 3	Ensure healthy lives and promote well-being for all at all ages
SDG 4	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
SDG 5	Achieve gender equality and empower all women and girls
SDG 6	Ensure availability and sustainable management of water and sanitation for all
SDG 7	Ensure access to affordable, reliable, sustainable and modern energy for all
SDG 8	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
SDG 9	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
SDG 10	Reduce inequality within and among countries
SDG 11	Make cities and human settlements inclusive, safe, resilient and sustainable
SDG 12	Ensure sustainable consumption and production patterns
SDG 13	Take urgent action to combat climate change and its impacts
SDG 14	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
SDG 15	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
SDG 16	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
SDG 17	Strengthen the means of implementation and revitalize the global partnership for sustainable development

Figure 1.3 List of the 17 Sustainable Development Goals (SDGs), adapted from (10)

In the same year, history was written in Paris: at the international climate conference, also called ‘COP 21’, the Paris Agreement was adopted. All nations committed themselves to change the world economy in a climate-friendly way. The aim is to limit global warming to below 2°C and, if possible, below 1.5°C compared to the pre-industrial level (11).

At the beginning of June 2019 the Sustainable Development Solutions Network (SDSN) together with the Bertelsmann Stiftung published the fourth edition of its Sustainable Development Report (12) with an overview presenting the performance of all countries in implementing the Agenda 2030 and their 17 Sustainable Development Goals (SDGs). The key findings of the study show, among other findings, that high-level political commitments made in 2015 remain unfulfilled and that the trends towards SDG 13, 14 and 15 are alarming. This calls for measures to be taken now in the area of mitigating climate change, especially on CO_2 emissions, species protection and biodiversity. The study also concludes that there is a need to raise social awareness about Agenda 2030 and its 17 goals. The ‘Fridays For Future’(13) movement with its, to this extent previously unseen, social commitment to sustainable development shows that the education system plays an essential role here (14).

As per the World Health Organisation (WHO), *“climate change is the greatest threat to global health in the 21st century”* (15). The most significant climate change impacts on human health have been illustrated by the CDC (Centers for Disease Control and Prevention) (Figure 1.4), showing that increased heat, more extreme weather, rising sea levels, and increase in CO_2 emissions have severe health consequences (16).

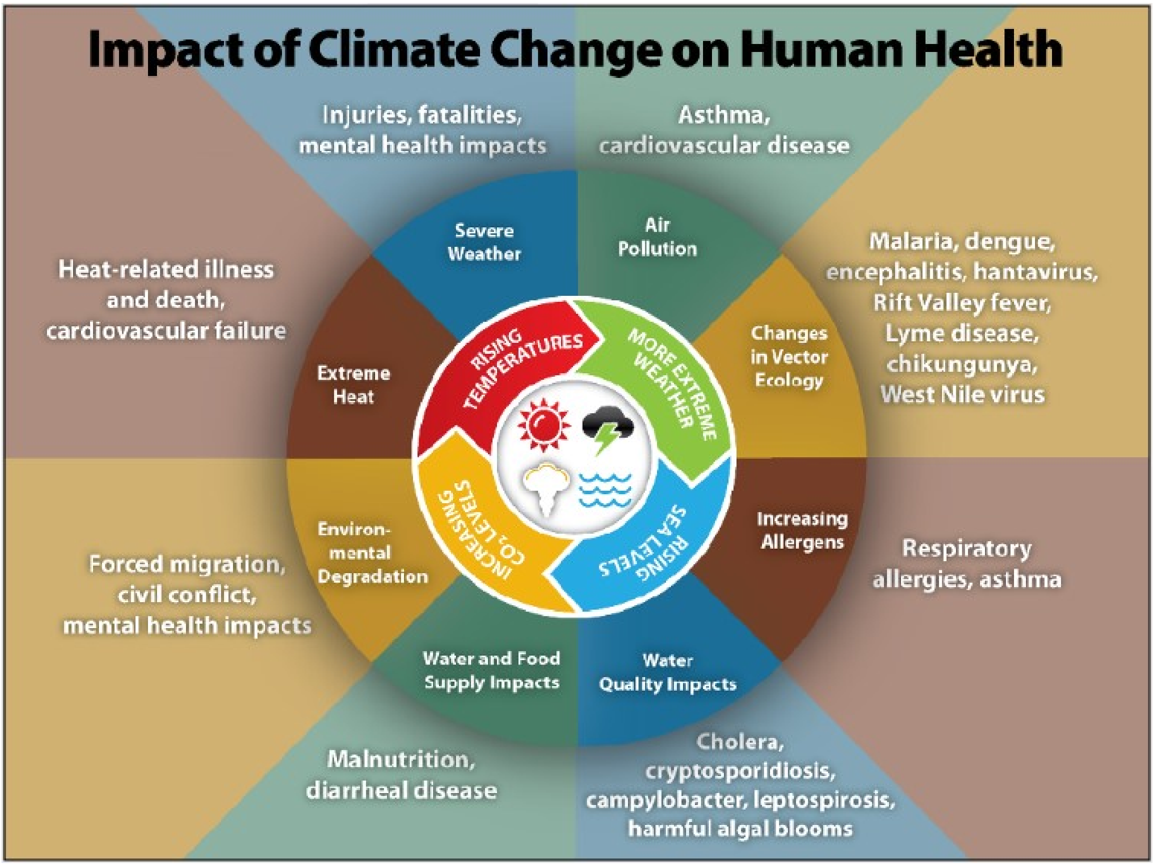


Figure 1.4 Impact of Climate Change on Human Health, figure taken from (16)
(Source: Center for Disease Control and Prevention (CDC), Available from: https://www.cdc.gov/climateandhealth/effects/default.htm)

The climate crisis affects the health sector in two ways: firstly, the burden on already stressed health systems is increasing, and secondly, the health sector itself is a significant emitter of greenhouse gases (17).

"Health sector facilities are the operational heart of service delivery, protecting health, treating patients, and saving lives. Yet health sector facilities are also a source of carbon emissions, contributing to climate change. The world's health sector facilities churn out CO_2 *through the use of significant resources and energy-hungry equipment. This is perhaps ironic — as medical professionals our commitment is to 'first, do no harm.' Places of healing should be leading the way, not contributing to the burden of disease."* said Tedros Adhanom Ghebreyesus, Director General of the World Health Organization (WHO), cited in the Health Care Without Harm (HCWH) Report (18).

In May 2019, Pichler et al. (17) published an international comparison of health care carbon footprints showing that *"The health care sectors of the 36 countries in our sample combined were responsible for 1.6 Gt of CO2 emissions or 4.4% of the global total in 2014 (35.7 Gt)."*

To achieve the Paris Agreement goal of keeping global warming below 2°C, the health sector has a responsibility to reduce its own emissions (17–19). Further to these remarkable numbers, the first Green Paper entitled 'Health Care's Climate Footprint' (18) was presented by Health Care Without Harm (HCWH) and ARUP in September 2019. Based on data from 43 countries, regional estimates (excluding Africa and the Middle East) of emissions could be produced, thus reporting the first-ever global estimate of the climate footprint of the health care system. One of the key findings of this report is that the USA, China, and EU are the largest emitters, responsible for more than half (56%) of the total global health care's climate footprint (18). The contribution to greenhouse gas emissions from health care is based on the consumption of energy, the disposal and use of products and transport systems. The sources of emissions can be divided into 3 areas: Scope 1 - direct emissions directly from the healthcare facility and its vehicles, Scope 2 - indirect emissions from purchased energy sources, and Scope 3 - emissions from the healthcare supply chain. These include the production, transport and disposal of goods, including medical devices and instrumentation. Further, this report outlines a series of measures that the Healthcare sector can take to support the goals of the Paris Agreement and yet achieve global health goals (18).

1.3 What academic hospitals and laboratories do to reduce their climate footprint

A number of environmental initiatives have been started to contribute to the reduction of the environmental footprint. Some examples of what academic hospitals and laboratories are doing to address the impact of climate change on health were presented in a report by the Accossiation of American Medical Colleges (20) and are summarized here.

Academic hospitals and clinical institutes in the USA, including, e.g. Harvard Medical School, announced a commitment towards decarbonization as well as transition to renewable energy (20,21). The University of California system for example is committed to achieve carbon neutrality by 2025 (22). The U.S. Green Building Council has developed a program for evaluating environmentally friendly buildings, known as LEED certification, and many hospitals have managed to achieve such certification (23). A number of energy-saving measures have been implemented, including the use of natural light, the use of LEDs, the installation of high-efficiency equipment and HVAC (heating, ventilation and air conditioning) occupancy sensors as well as the implementation of demand reduction strategies (24). Even if measures to improve energy consumption involve investment, the savings can be significant (20).

Another example in regard to environmentally friendly buildings is the Med Campus of the Medical University of Graz. It is the first research and laboratory building in Austria that has achieved the German Sustainable Building Council (Deutsche Gesellschaft für Nachhaltiges Bauen – DGNB) pre-certification in gold (25). The DGNB certification system is another international certification system for sustainable buildings (26).

The measures to counteract the effects of climate change on health are not only related to buildings. For example, Emory University Hospital has planted three times as many trees as were destroyed to build a LEED-certified tower (20,27). Furthermore, cycling, public transport and carpooling are promoted, and environmental awareness is fostered through education, incentive programs and volunteer events. Measures are also taken in the area of recycling and waste avoidance and, in the case of food, ecological and sustainable food is promoted (20).

Especially in the field of laboratories, which are known to be more energy-intensive than any other sector besides data centers and can consume 3-5 times more energy than office premises (28), so-called 'Green Lab Programs' are working to implement measures for energy, water and waste reduction. Competitions such as 'Shut the sash' from Harvard's Green Lab program (29) encourage people to keep fume hoods closed when not in use. By reducing the exhaust airflow, energy is saved and reduces significant amount of greenhouse gas emissions and costs (29). Another energy-saving measure concerns the temperatures in freezers. Ultra-low temperature (ULT) freezers are usually set to -80°C, although the setpoint of -70°C uses less energy while safeguarding samples (30). At the campus of the University of Colorado Boulder, around 50% of ULT freezers are set nowadays to -70°C in comparison to only about 3% in 2010 (31).

In the UK, at University College London, a group of universities have developed a new tool to improve sustainability and efficiency in the laboratory. This instrument is called LEAF and stands for Laboratory Efficiency Assessment Framework (32). It contains criteria at bronze, silver and gold levels covering the topics waste and recycling, equipment management, purchasing and others, and allows to quantify savings and impact in terms of costs and carbon. This tool aims to provide a comparable standard of good practice and to demonstrate the positive impact of the efforts of a broad group of universities. It has been tested with 16 other research institutions in a pilot project at University College London in 2018-2019 and will be further developed (32).

Many Green Lab Programs work with My Green Lab, a non-profit organization based in California USA, that helps to establish and certify sustainable laboratories. Since 2017, My Green Lab together with the International Institute for Sustainable Laboratories (I^2SL) is running the International Freezer Challenge, stimulating and challenging labs around the world to reduce the energy consumption for cold storage by implementing energy-saving practices (33,34).

1.4 Biobanking in healthcare

Biobanking, with its processes of collection, storage and distribution of a variety of human biological samples (further referred to as samples) and corresponding well-annotated data for further use in research, is a fundamental resource for biomedical advancement, disease prevention as well as better healthcare for those individuals suffering from a disease (35,36). Disciplines like Translational Cancer Research require significant amounts of cases, including human samples and associated data. Biobanks can support these needs as a result of collection, storage and distribution of, for example, 'leftover' residual samples from clinical care in hospitals, like samples from pathological examinations or clinical laboratory testing, which have been primarily obtained for diagnostic and therapeutic needs (37,38).
Biobanks became increasingly important as technological advancement led to a growth of research demand and therefore also the need for more samples of high quality arose (35). Whereas the term 'Biobank' is quite new and could first time be found in scientific literature in 1996 (39), the process of collection and storage of human biological material is going back for decades with collections of significant historical importance (40). As an example, the collected serum samples from unresolved pneumonia-like cases collected by the CDC (Centers for Disease Control and Prevention) decades before the outbreak in 1976 in Philadelphia have led to the finding of the Legionnaire's Disease bacterium. This is just one example beside others including HIV, Hepatitis and Hantavirus sample collections demonstrating the importance of long-term biobanking activities in research and healthcare (40).

While biobanking activities started with mostly small collections for particular research projects at universities, there have been tremendous changes over the past thirty years including the evolution of population-based biobanks, commercial biobanks and recently also virtual biobanks to connect researchers around the world to share and locate samples and data from various biobanks using web-based applications and specialized software. Besides the growing number of samples stored in biobanks not only the amount of connected data increased but the data got more complex. Whereas in the past only basic data like diagnosis and collection-date have been documented, today's biobanks hold large sets of information containing a wide range of donor information including genetic, proteomic and other 'omics' data (41) as well as records of pre-analytical factors and variations related to the collection, processing, storage and shipping of samples (42).

1.4.1 Definition and types of biobanks

Due to the diversity of biobank types, several definitions of the term 'Biobank' can be found in literature. Some of these are restricted to human samples, while others cover all types of biological samples independent of species. Other terms like 'Biomolecular Resource Center', 'Biological Resource Centers' or 'Biorepository' are also commonly used.

The Biobanking and Biomolecular Resources Research Infrastructure – European Research Infrastructure Consortium (BBMRI-ERIC) defines a biobank in the following way:

"Biobanks (and Biomolecular Resources Centres) means collections, repositories and distribution centres of all types of human biological samples, such as blood, tissues, cells or DNA and/or related data such as associated clinical and research data, as well as biomolecular resources, including model- and micro-organisms that might contribute to the understanding of the physiology and diseases of humans"(43).

Based on the findings of their survey in 2013, Hewitt and Watson (39), propose the following definition of the term 'biobank':

"A biobank is a facility for the collection, preservation, storage and supply of biological samples and associated data, which follows standardized operating procedures and provides material for scientific and clinical use"(39).

Another definition can be found from the Organisation for Economic Cooperation and Development (OECD):

"Biological resource centres are an essential part of infrastructure underpinning biotechnology. They consist of service providers and repositories of the living cells, genomes of organisms and information relating to heredity and the functions of biological systems…BRC must meet the high standards of quality and expertise demanded by the international community of scientists and industry for the delivery of biologic information and materials. They must provide access to biological resources on which R&D in the life sciences and the advancement of biotechnology depends"(44).

An extended definition by Huppertz (45) is adding the importance of quality as well as ethical and legal issues to the term 'Biobank':

"Biobanks are facilities for the systematic and structured collection, storage and distribution of high quality biological samples and their associated (clinical) data for research purposes, embedded in an ethical and legal framework"(45).

All those definitions have in common that biobanking refers to the collection, processing, storage, and distribution of samples and data.

The various definitions of the term 'Biobank' apply to different types of collections and therefore indicate the diversity of Biobank types which can be classified in various ways.
When only considering human-based Biobanks, Gottweiss and Zatloukal (46) are distinguishing four types of biobanks:

- *Clinical case/control biobanks* (Collections containing samples from non-disease controls and samples from patients suffering from a specific disease, for example tumor-biobanks)
- *Longitudinal population-based biobanks* (Collections containing samples from the general population monitored over a long period of time, for example the UK Biobank)
- *Population isolate biobanks* (Collections characterized by a consistent genetic basis as well as ecological conditions of the target population, for example the Icelandic Biobank)

- *Twin registries* (Collections containing samples from mono- and dizygotic twins which can be utilized to differentiate whether a disease has a genetic or non genetic origin.

Watson (47) proposed a classification scheme related to the design and function of a biobank. Based on that approach the Canadian Tumour Repository Network (CTRNet) developed a classification scheme built on four sub-elements: Scale, Data Format, Leadership and User Type. 'Scale' is related to the number of samples and therefore to the size of the collection. 'Data Format' is referring to whether or not the sample data can be linked to the donor, including the availability of informed consent. The sub-element 'Leadership' indicates whether the Biobank is managed by a single investigator, a group, an institution or an organization whereas 'User-Type' is referring to the scope of research use, like a clinical trial or a single specific project (47).

Besides those examples on classification schemes, Biobanks can be distinguished according to their business model and type of organization (profit or non-profit), their ownership (academic or non-academic) and their purpose (research, diagnostic, therapeutic) (45).

While biobanking in healthcare is mainly associated with 'human biobanks' containing samples derived from humans, also 'non-human biobanks' like animal biobanks (e.g. the VetBiobank at the Vetmeduni in Vienna, Austria), seed biobanks (e.g. the Svalbard Global Seed Vault on the island of Spitsbergen, Norway) and fungal biobanks (e.g. the CBS fungal biobank at the Westerdijk Fungal Biodiversity Institute in Utrecht, Netherlands) exist, just to name a few examples.

1.5 Biobanking key activities

All of the various definitions of the term biobank in Chapter 1.4.1 show that the five key activities of biobanking include collection, preservation, processing, storage and distribution of samples and related data considering quality management as well as ethical and legal compliance (Figure 1.5). Various types of samples, not only from humans but also from animals, plants or even soil, such as blood and other body fluids, tissues, prokaryotic and eukaryotic cells, isolated biomolecules or seeds, are collected in biobanks with the aim of providing access to research and development in both academia and industry (48).

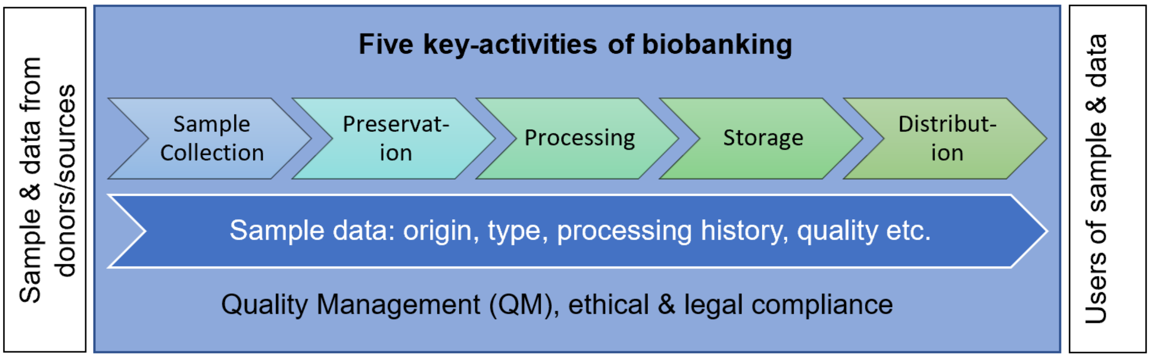


Figure 1.5 Five key activities of biobanking adapted from (48)

A typical lifecycle of samples in a biobank can be linked to three main activities including the collection and processing, storage, and preparation with subsequent distribution of samples (Figure 1.6). Those activities further consist of a series of different steps. Depending on the sample type, the collection strategy and the future analysis the collection procedures, storage conditions and processing will vary (49,50).

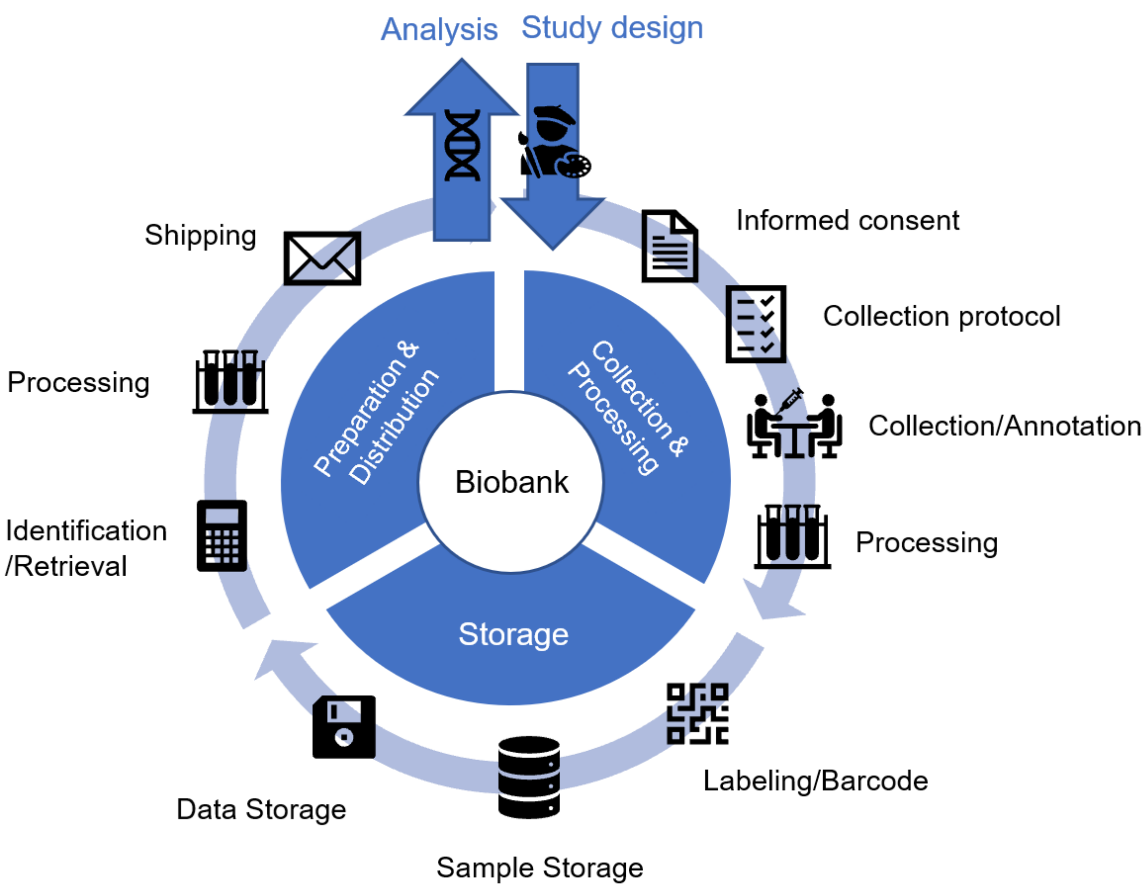


Figure 1.6 A typical lifecycle of samples in a biobank, adapted from (49,50)

1.6 Sample storage conditions

To ensure the stability, quality, integrity and function of samples, robust storage procedures are required in biobanking. The suitability of samples for the intended future purpose must be guaranteed, this characteristic is the so-called 'fit for purpose'. The type of preservation and the temperature of storage are pre-analytical variables, beside others, that can influence the later performance of samples. Which storage conditions are applied depends primarily on the type of samples, their use, duration of storage and analytical methods. In addition, there are also the aspects of costs, infrastructure and logistics involved (50,51).

Storage temperatures can range from room temperature to chilling/hypothermic, ultra-low and cryogenic temperatures between +2°C and -196°C. The most widespread method for preservation of samples is freezing and storage at appropriate low temperatures to prevent degradation. Some other preservation methods include chemical fixation, drying, lyophilization and dry storage at room temperature, e.g. storing formalin-fixed paraffin-embedded (FFPE) tissue samples or collection of blood spots on filter paper cards. Considering room temperature storage, also purified DNA and RNA as well as other samples including saliva, feces, blood, tears, cells and tissue can be stored using new technologies that have been developed (49,52–55).

The classification scheme of temperature ranges for the storage of samples varies in the literature. For the purpose of this study, the classification of temperatures and generally applicable storage conditions for some of the most common sample types stored in biobanks can be found in Table 1.1.

Table 1.1 Classification of storage temperatures adapted from (49,52,56)

Temperature in °C	Storage condition	Recommended for e.g.
+18 to +20	Room Temperature	Storage of slides and formalin-fixed, paraffin-embedded (FFPE) tissue
+2 to +8	Refrigerator 'chilling/hypothermic'	Processing and transport of fresh samples
-15 to -40	Freezer 'low temperature'	Short-term DNA storage

-65 to -85	Freezer 'ultra-low temperature'	Long-term DNA storage, urine, blood and blood fractions (plasma, serum, etc.)
-150 to -180	Liquid Nitrogen LN_2 (vapour phase)	Storage of tissue, preservation of cellular viability
-196	Liquid Nitrogen LN_2 (liquid phase)	Storage of living cells

1.7 Storage systems for samples at ultra-low temperatures

As mentioned before in Chapter 1.6, robust storage conditions are crucial to ensure high-quality and 'fit for purpose' samples in biobanking. Storage temperatures like in vapour phase (-150°C) or liquid phase (-196°C) of liquid nitrogen (LN_2), needed for cellular samples, can be achieved with liquid nitrogen freezers. The most common liquid samples such as serum, plasma and DNA can be securely stored for long term at ultra-low temperature in mechanical freezers (49), so-called ultra-low temperature (ULT) freezers typically operating between -70°C and -80°C (57). Individual stand-alone ULT freezers are available as upright and chest models in a wide range of sizes, with adjustable inner cabinet compartments for storage of boxes, racks as well as larger items depending on storage capacity needs (58). The first ULT freezers were designed to reach -60°C (59), around 20 years ago scientists called ULT freezers 'the minus 70' (30) and today technical development provides ULT freezers with temperatures down to -86°C or even lower (57,60). It seems as if this is driven by the competition and marketing strategies of the industry rather than scientific necessity (30). These ultra-low temperatures are typically achieved by a mechanical two-stage cascade refrigeration system, consisting of a high-stage (1^{st} Stage) and low-stage (2^{nd} Stage) compressor, a cabinet for storage of samples, an evaporator, a condenser and refrigerants (57,61). A schematic illustration of a mechanical two-stage cascade refrigeration system is shown in Figure 1.7.

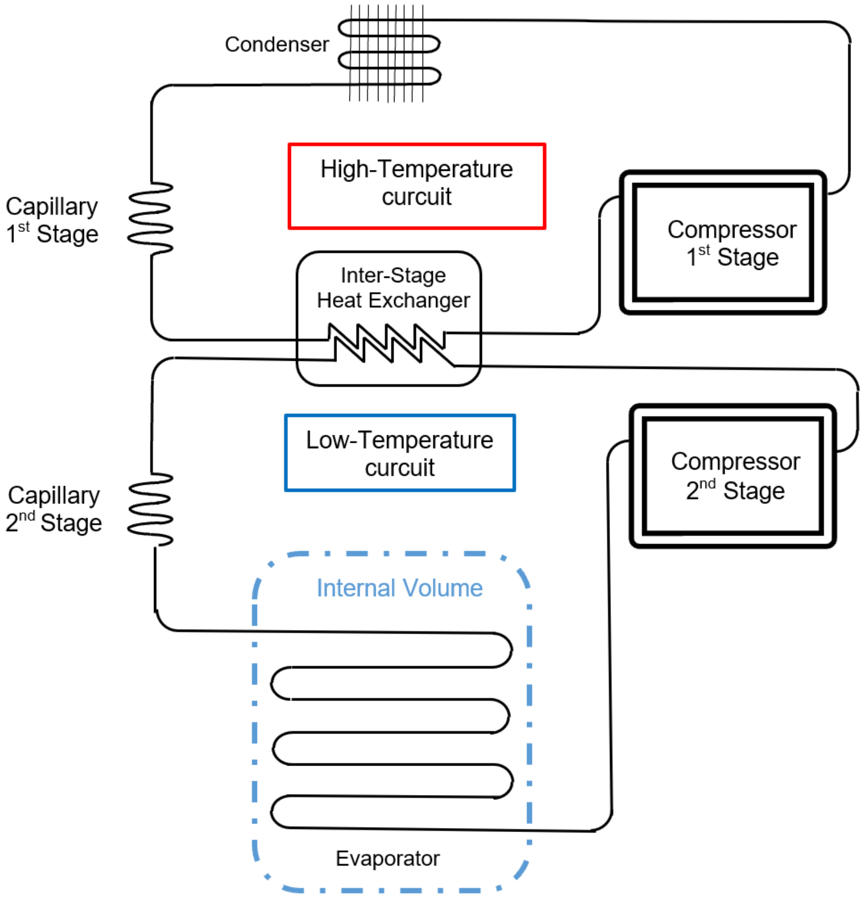


Figure 1.7 Schematic illustration of a mechanical two-stage cascade refrigeration system, adapted from (61)

Mechanical (compressor-based) ULT freezers are connected to the commercial power system and are dependent on an emergency power system or an emergency backup system with liquid nitrogen (LN_2) or liquid carbon dioxide (CO_2) in case of a longer power failure (52). While ULT freezers are also available with LN_2 cooling systems independent of a constant power supply, the use of mechanical ULT freezers in biobanks is widespread, poses less risk to staff and provides constant, uniform top-bottom cabinet temperature for long-term storage of samples (62).

Over decades, manufacturers have achieved advances in the efficiency and environmental performance of ULT freezers through improvements in the design of components such as compressors, controllers, isolation, storage cabinet interior and the use of natural refrigerants (63,64) as well as the use of advances in the operation of ULT freezers, e.g. water cooling instead of air cooling (65). Manufacturers have replaced hydrofluorocarbons (HFCs) with high global warming potential (GWP), such as R508b and R404a, used as refrigerants in ULT freezers with natural green refrigerants such as R290 (propane) and R170 (ethane)

(64,66) in accordance with EU Regulation No. 517/2014 also know as the f-gas regulation (67). The latest innovation in ULT freezers uses a compressor-less refrigeration system design using a free piston Stirling engine promising significant reduction in energy use (61). Nevertheless, ULT freezers are among others the most energy-intensive devices in scientific laboratories (28,68), as well as in biobanks, where depending on the type, collection size and purpose a considerable number of ULT freezers may be operated. A standard individual stand-alone 25 cubic-feet (700 liters) ULT freezer consumes approximately 20kWh per day, which is the average consumption of a family household in the USA per day (57,69). In comparison, an energy-efficient model within the same size, holding an 'Energy Star' certification that is relatively new for ULT freezers, uses less than 10kWh per day (70,71).

Besides individual stand-alone ULT freezers, a series of ULT freezers can be connected to a central mechanical cooling unit in a so-called 'cascade freezer system'. Further, walk-in freezers and automated storage systems for convenient storage and retrieval of samples at various temperatures, including ultra-low temperatures, have been developed with storage capacities from thousands to millions of samples (49,52).

In addition to storage systems, like ULT freezers, required to achieve robust ultra-low temperature conditions, suitable sample storage vials/containers and storage boxes/racks are required for the long-term storage of samples in biobanks. Certain considerations and requirements must be taken into account when selecting suitable sample storage vials, including high quality of material, labeling and barcode options, filling capacities, stability at low temperatures, compatibility with robotic systems, space saving and costs (72).
A number of sample storage solutions are available on the market comprising a large variety of sample vials with various coding options and filling capacities ranging from e.g. 0.2ml up to 7.00ml sample vials in 24-, 48-, 96-format ANSI/SLAS standard storage racks as well as in 9x9, 10x10 or 14x14 formats, well known as 'cryo boxes' (73,74). Latest innovations offer racks in 'high density' format for increased storage capacity and space saving (75).

1.8 Sustainability in biobanking and laboratory sustainability

Rising costs are challenging the sustainability of healthcare systems worldwide and since biobanks represent significant resources for the advancement of biomedical research and better healthcare, financial sustainability is a crucial issue to keep biobanking activities running for the long term (76).

Similar to the three pillars of sustainability in a general sense, as mentioned at the beginning of this introduction in Chapter 1.1, sustainability in biobanking can also be applied to three main dimensions. The financial (in analogy to economy), operational (in analogy to environment) and social (in analogy to society) dimension (77,78). Dealing with each dimension of sustainability in biobanking is a difficult task due to the complexity and the many different types and processes of biobanking, as well as the relative importance of the various dimensions of sustainability among stakeholders (78).

Watson et al. (78) have defined several key areas among the three dimensions of sustainability in biobanking. The financial dimension includes the areas: market strategy, stakeholder needs and brand recognition, while the development of a strategic plan is mentioned as a major component. The operational dimension relates to the efficiency of biobanking input, output and internal processes, including e.g. patient enrollment, optimizing sample processing and improving response time to requests. The social dimension includes acceptance by stakeholders, including donors and public society, and a commitment to recognized standards of practice (78). The three dimensions of sustainability in biobanking with the associated key areas are illustrated in Figure 1.8.

Figure 1.8 The three dimensions of sustainability in biobanking with the associated key areas, adapted from (78)

The approaches and ideas for sustainability in biobanking vary (76–79) and the published work being done includes a number of tools, recommendations and practices to help biobanks to tackle sustainability, a large number focusing on financial sustainability (80).

A Special Issue in the Journal 'Biopreservation and Biobanking' (Volume 17, Issue 3 June 2019) addresses the topic of sample utilization, as underutilization became globally a major concern in biobanking operations, pointing to the need of growing efforts in maximizing the use of existing sample collections.

Biobanking being a relatively new and dynamic field has developed rapidly from early stages primarily focusing on high numbers of samples and data, to a shift on focusing on quality of data and samples and further addressing stakeholders' needs and sustainability (81). The development of biobanks has been described by Simeon-Dubach and Watson (81) as transformation of biobanking from stage 1.0 to stage 2.0 and ultimately to stage 3.0.
The development of biobanking from simple sample collections to highly professionalized and standardized organizations is also reflected in the establishment of several international networks and societies in the field of biobanking, including BBMRI-ERIC (Biobanking and Biomolecular Resources Research Infrastructure – European Research Infrastructure Consortium) (82), ISBER (International Society for Biological and Environmental Repositories) (83) and ESBB (European, Middle Eastern & African Society for Biopreservation and Biobanking) (84), just to name a few.

In order to maintain high quality, consistency, and support harmonization throughout the collections, processes and services of biobanks and therefore support sustainability, several Best Practices and Guidelines are available. The three latest and most comprehensive ones are:

- ISBER Best Practices: Recommendations for Repositories, 4th Edition, 2018 (52) (including the Addendum 1: Liquid Nitrogen-Based Cryogenic Storage of Specimens, 2019) (85)
- IARC Technical Publication No.44, Common minimum technical standards and protocols for biobanks dedicated to cancer research, 2017 (50)
- NCI Best Practices for Biospecimen Resources, 2016 (86)

Beside Best Practices and Guidelines like those mentioned above, the ISO 9001 Standard dedicated to Quality Management and a number of Technical Specifications by the European Committee for Standardization (CEN/TS) dedicated to pre-analytical sample processing are applicable in the field of biobanking (87). In 2018, the ISO 20387 Standard was issued explicitly dedicated to the quality, competence and impartiality of biobanking operations (88).

The environmental impact has not yet been addressed in the literature on sustainability in biobanking, although it has been mentioned as an aspect on the operational level when it comes to efficiency in operating a biobank (77). So far there is no data on the environmental impact of biobanks available. However, biobanks with their high-tech infrastructure have recently attracted attention in the field of laboratory sustainability. In an article posted by the UKCRC Tissue Directory and Coordination Centre as well as the University College London (UCL) in 2019, Martin Farley, Sustainable Laboratory Advisor at the University College London addressed environmental sustainability in biobanking: *"Lab sustainability is a growing field, which focuses on reducing the waste and pollution produced in typical science labs. Science labs are extremely energy intensive, and have been shown to utilise up to 10 times more energy than typical academic spaces. It is not uncommon in science-intensive universities for 60%+ of all energy consumed to go to laboratory buildings. In terms of waste, a study at the University of Exeter estimated that labs may be responsible for ≈2% of the world's plastic waste. These plastics are typically incinerated at high temperatures and thus go directly into our atmosphere"*(89,90).

How sustainability of labs is related to biobanking and freezers, was argued by Martin Farley as following: *"Biobanking has captured the attention of many working in sustainable labs. Not only are biobanks growing to match the requirements of larger sample-set analysis, but cold storage in general can be extremely energy intensive. One ultra-low temperature (ULT) freezer operating at -80°C will consume as much or more energy than the average UK household! Freezer manufacturers have even reduced ULT operational temperatures from -70°C to -80°C, seemingly to outcompete competitors (today many units are marketed as -86°C or colder). This temperature difference has large energy implications, as -80°C ULTs use 30% more energy than a freezer at -70°C. Although colder temperatures do allow increased reaction time during power losses, studies have shown these effects to be minimal particularly with improvements in insulation"*(89,90).

Beside freezer practices, Farley (89,90) also commented on sample management practices and mentioned 'The Laboratory Efficiency Assessment Framework' (LEAF) an university-based engagement tool that covers a comprehensive range of measures in terms of sustainable practices in laboratories including cold storage (32).

1.9 Research question and hypothesis

The background described in the previous chapters of the introduction part leads to the research questions of this thesis:

What are the opportunities to reduce the environmental impact of manual sample storage at ultra-low temperatures?

Manual sample storage at ultra-low temperatures is only one example suitable to be addressed when it comes to environmental sustainability in biobanking beside others like automation, liquid nitrogen storage, water and waste management in general, HVAC (heating, ventilation and air conditioning) management, energy efficiency recovery and much more, which would go beyond the scope of this thesis and will therefore not be addressed.

I anticipate that opportunities to reduce the environmental impact of manual sample storage at ultra-low temperatures include measures, recommendations and considerations related to the management of ULT freezers under the consideration of factors affecting the performance and energy consumption of ULT freezers, as well as the management of samples stored at ultra-low temperatures and considerations related to the purchasing of storage systems and consumables.

The purpose of this thesis is to identify opportunities to reduce the environmental impact of manual Ultra-Low Temperature (ULT) storage of samples in biobanks, with the overall aim for biobanks to consider practices contributing to the Sustainable Development Goals and to emphasize the topic 'Environmental Sustainability in Biobanking' addressing the following sectors: the scientific and technological community as well as business and industry and to contribute to growing a culture of sustainability in biobanking.

2 Methods

2.1 PubMed search

To identify relevant literature dealing with environmental sustainability in the field of biobanking, a PubMed search has been performed on October 23rd, 2019 and October 24th, 2019, without success. The PubMed search has been repeated on November 21st, 2019, using the following keywords:

- (Biobank* OR Biorepository OR Bioresource center)

AND

- Sustainability

AND

- (Sample Storage OR Liquid Samples OR Biospecimens)

AND

- (Ultra low temperature OR ULT)

However, this PubMed search identified 0 findings (Table 2.1). When reducing the number of keywords it became obvious that the vast majority of work in the area of sustainability in biobanking has been done on the operational and social levels including financial aspects, acceptance, utilization and process management, but not on environmental sustainability. Therefore, the above PubMed literature search has not been sufficient to deliver sources to answer the research question of this study.

Moreover, in short interviews stakeholders and experts in the field confirmed that so far there is no publication on environmental sustainability available in the field of biobanking (personal communication, Marianne K. Henderson (Senior Advisor for biobanking at the National Cancer Institute, U.S. Department of Health and Human Services), Daniel Simeon-Dubach (CEO Medservice biomedical & biobanking consulting, Switzerland) and Berthold Huppertz (Former Director of Biobank Graz, Medical University of Graz, Austria)).

Table 2.1 PubMed search from 21.11.2019

Query	Items found
"Search (((((((Biobank* OR Biorepository OR Bioresource center))) AND Sustainability)) AND (Sample Storage OR Liquid Samples OR Biospecimens))) AND (Ultra low temperature OR ULT)"	0
"Search (((((Biobank* OR Biorepository OR Bioresource center))) AND Sustainability)) AND (Sample Storage OR Liquid Samples OR Biospecimens)"	32
"Search (((Biobank* OR Biorepository OR Bioresource center))) AND Sustainability"	106
"Search (Biobank* OR Biorepository OR Bioresource center)"	11066

2.2 Google search

In order to identify sources available to answer the research question of this master thesis, initiatives and programs related to laboratory sustainability have been identified by performing a Google search. Using the keywords: “green lab sustainability” a respective search was performed on November 6th, 2019. To get the most recent findings, the search results have been restricted to the period of 01.01.2018 to 06.11.2019, resulting in 215 hits.

2.2.1 Selection process

Out of these 215 hits, 42 initiatives related to Laboratory Sustainability have been identified. Out of those, 31 university-based sustainability programs or so-called ‘Green Lab Programs’, three commercial organizations and eight other organizations were identified by visiting the websites and skimming through their content.

Although the three identified commercial organizations (Green Lab Associates – UK, Green Light Laboratories- UK, NIUB Nachhaltigkeitsberatung – DE) offer consultation and assessment service there have been no open resources available on their websites to retrieve sufficient information on measures related to ultra-low temperature sample storage. Therefore, they have been excluded.

The eight identified other organizations working in the field of laboratory sustainability include the non-profit organization ‘My Green Lab’, mainly focusing on sustainable laboratory practice, and the International Institute for Sustainable Laboratories (I^2SL), offering comprehensive resources and education for a wide range of topics covering the design, engineering, operation and use of laboratories and other high-tech infrastructures. All of the other organizations have not been included in the evaluation as an own source. However, they are frequently cross-linked and referred to within the frame of university-based sustainability programs. An example is the ‘International Laboratory Freezer Challenge’ (Freezer Challenge), a competition that has been running by My Green Lab and I^2SL since 2017 to promote and facilitate measures to reduce the environmental impact of sample storage.

To reflect what measures, recommendations and considerations are promoted and practiced in university-based scientific research to meet environmental responsibility, the selection for evaluation was restricted to university-based sustainability programs meeting the following criteria:

- a framework for managing environmental responsibilities is established at the university
- the sustainability activities cover laboratory practices
- measures, recommendations and considerations are related to sample storage and ultra-low temperature (ULT) freezers

Nine out of the 31 university-based sustainability programs had to be excluded due to one of the following reasons faced during the evaluation process:

- Not all website content was available, e.g. ‘Page not found’
- Website only contained weblinks to other sources
- Content was restricted to a log-in area and therefore publicly not available
- Website only contained very little information and therefore no sufficient information on measures related to ULT sample storage could be retrieved

Two additional university-based sustainability programs have been added. These programs were not found during the initial web search but during the further evaluation and met the inclusion criteria described above. This resulted in a total number of 24 university-based sustainability programs included in the evaluation for this study. The list including weblinks and date of access can be found in **Annex-A.**

2.3 Evaluation process and categorization of results

The evaluation of the university-based sustainability programs has been carried out from November 18th, 2019 until January 8th, 2020.

In the first step of the evaluation process, the websites of the universities have been reviewed, and actions (measures, recommendations and considerations) towards more sustainable storage of samples at ultra-low temperatures were identified from a variety of sources, which have been publicly available, including:

- Best practices and recommendations for sustainable lab practice 'Green Lab Guides'
- Freezer Management & Maintenance Guides
- Posters promoting sustainable lab practice
- Green Lab Assessment forms
- Reports & Case Studies on investigations of ULT freezers
- Blog Posts
- Presentations from workshops
- Purchasing Guides

In the second step of the evaluation, four categories for the classification of actions (Table 2.2) towards more sustainable storage of samples at ultra-low temperatures have been defined.

Table 2.2 Categories for classification of actions

Category for classification	Description
A “Green” Sample Management	Measures, recommendations and considerations related to sample storage (e.g. storage temperatures, storage containers, sample inventory systems)
B “Green” Freezer Management	Measures, recommendations and considerations related to ULT freezers (e.g. temperature setpoints, operation, location and monitoring of ULT freezers)
C Freezer Maintenance	Measures, recommendations and considerations related to the maintenance of ULT freezers
D “Green” Procurement	Measures, recommendations and considerations related to the purchasing of ULT freezers as well as consumables for sample storage

In the third step of the evaluation process, a coding system was developed. These codes have been further assigned to the relevant category of actions (Table 2.2). The development of the coding system has been done by carefully reading the resources line by line. For each text passage relevant to the research question, a specific code was assigned. If a new relevant text passage did not match to one of the already defined codes, a new code was defined, existing ones were expanded or combined if the measure, recommendation or consideration found was very closely related. This procedure is similar to the process of inductive category creation, according to Mayring (91). The developed coding system is shown in Table 2.3.

Table 2.3 Coding system for the assignment of relevant actions to subject areas

Category for classification of actions	Code #	Code name OR ‘Subject area’	Code Description OR ‘Subject area description’
A "Green" Sample Management	A1	Inventory system	Clear, organized and up to date sample record system
	A2	Sample clear-out	Removal of unused and unnecessary samples
	A3	Storage boxes and racks	Containers for organization and storage of sample vials

	A4	Sample vials	Containers for storage of samples
	A5	Sample labeling	Labeling of stored sample vials
	A6	Sample consolidation	Arrangement of samples at smallest possible footprint
	A7	Storage temperature	Choice of sample storage temperature
B "Green" Freezer Management	B1	ULT freezer manager	Person in charge for managing the ULT freezer
	B2	ULT freezer location	Location where the ULT freezer is positioned
	B3	Back-up ULT freezer setpoint	Choice of back-up ULT freezer temperature
	B4	ULT freezer setpoint	Choice of ULT freezer temperature
	B5	Airflow	Airflow around ULT freezer
	B6	ULT freezer door closing	Proper closing of ULT freezer door
	B7	ULT freezer space	Management of ULT freezer inner space
	B8	Temperature monitoring	Monitoring and logging of ULT freezer inner temperature
	B9	Energy monitoring	Monitoring of ULT freezer energy usage
	B10	ULT freezer alarm	Alarm system installed with ULT freezers in case of power-loss, breakdown, failure or bad performance
	B11	ULT freezer space sharing	Offering free ULT freezer space to others
	B12	Energy reduction device	Installation of energy reduction device to ULT freezer
	B13	Emergency instructions	Handling instructions in case of ULT freezer failure or breakdown
	B14	ULT freezer consolidation	Combining contents of two ULT freezers in one ULT freezer
	B15	ULT freezer unplugging	Unplugging ULT freezers not in use
C Freezer Maintenance	C1	Preventive maintenance plan	Scheduling & arranging preventive maintenance
	C2	ULT freezer frost removal	Removing of ice and defrosting of ULT freezer
	C3	ULT freezer filters and vents care	Cleaning of filters and vents of ULT freezer

	C4	ULT freezer seals care	Cleaning and replacement of ULT freezer seals
	C5	ULT freezer heat exchange coils care	Cleaning of ULT freezer heat exchange coils
D "Green" Procurement Considerations	D1	Old ULT freezers	Replacing or removing old ULT freezers
	D2	Incentive program	Initiative towards replacement and rationalization of ULT freezers
	D3	Energy-efficient ULT freezers	Purchasing energy-efficient ULT freezers
	D4	Eco-Labels	Labels for ULT freezers and consumables that meet certain environmental management criteria

2.4 Organization of data

A matrix was set up, indicating with the symbol ‘X’ in which related subject area, actions (measures, recommendations and considerations) towards more sustainable storage of samples at ultra-low temperatures could be found in the evaluated university-based sustainability programs. This matrix facilitates the representation of the frequency of actions found in all evaluated university-based sustainability programs as well as the number of actions mentioned for each of the university-based sustainability programs in total and per category.

All actions were sorted by category, summarized in a table, and described by reducing the content of all actions to its key statements.

2.5 Comparison to ISBER Best Practices

After the evaluation of the university-based sustainability programs, the latest and most comprehensive internationally available Best Practices Guide corresponding to biobanking activities has been analysed to compare whether the actions towards more sustainable storage of samples at ultra-low temperatures found in the university-based sustainability programs are mentioned. Therefore the 13 sections (Section A-M) of the ISBER Best Practices document - 4th Edition, 2018 (52), were examined. First, those sections of the ISBER Best Practices relevant to one of the 31 actions were assigned to the related subject area as defined in Table 2.3. In a second step, the degree of correspondence (level of correspondence) between the actions found in the university-based sustainability programs and ISBER Best Practices was determined and assigned according to the definitions in Table 2.4.

Table 2.4 Definition of terms for correspondence levels and examples of assigning correspondence levels to compared actions

Level of correspondence to action found in university-based sustainability programs	Indication symbol	Example of related subject area and action to be compared	ISBER Best Practices wording example 1	ISBER Best Practices wording example 2
Match The principle of recommendations in ISBER Best Practices is substantially similar, identical or goes beyond.	x	**A1: Inventory System -** Keeping clear, good organized and up to date sample records in an inventory system.	**Section D5: "**Repositories should develop a complete records management system to track all repository operations."(52)	**Section I2:** A "Computer-based inventory system should be in place to track the location and pertinent annotation of every specimen in the repository."(52)
Context variation The subject area is mentioned in ISBER Best Practices, but with variations in context.	o	**A4: Sample vials** - Maximizing sample container (sample vial) efficiency by choosing the minimal required sample vial size in a high-density format.	**Section K4:** "During selection of container type, consideration should be given to the long-term use, standardization and applicability to new platforms, and automation."(52)	**Section C4.1:** "The choice of labware size and manufacturer is optional, but at a minimum, a unique identifier that can be read electronically (barcode, RFID, etc.) should be on each specimen as many downstream processes can only be automated if the specimens have a barcode label."(52)
Not mentioned Neither principle of action nor subject area is mentioned in ISBER Best Practices.	\	**B9: Energy monitoring -** Monitoring ULT freezer energy usage with a power meter device.	N/A	N/A

3 Results

3.1 The evaluated university-based sustainability programs

24 university-based sustainability programs (Green Lab Programs) were selected for evaluation to identify actions, in the form of measures, recommendations and considerations, to meet environmental responsibility related to sample storage and ULT freezers promoted and practiced in university-based scientific research (Table 3.1). Out of those 24 university-based sustainability programs 17 (71%) are from the United States, five (21%) are from the United Kingdom, one (4%) is from Canada and one (4%) is from Australia.

Table 3.1 The evaluated university-based sustainability programs

Nr.	Name of the University	Country	Name of the university-based sustainability program
1	University of Bristol	UK	Sustainable Science and Green Labs
2	University of Cambridge	UK	Green Labs
3	University College London	UK	LEAF – The Laboratory Efficiency Assessment Framework
4	The University of Edinburgh	UK	Social Responsibility and Sustainability
5	Kings College London	UK	Sustainable Labs
6	University of California, Davis	USA	Green Lab Program
7	University of California San Francisco	USA	UCSF Green Labs
8	University of Colorado Boulder	USA	CU Green Labs Program
9	Cornell University	USA	Green Lab Program
10	University of Michigan	USA	Sustainable Labs
11	University of Pennsylvania	USA	Green Labs @ Penn Guide
12	Stanford University	USA	Cardinal Green Labs
13	University of Washington	USA	Green Laboratory Program
14	Harvard University	USA	Green Labs
15	The Pennsylvania State University	USA	Green Labs
16	Emory University	USA	Green Labs at Emory

17	University of Virginia	USA	Green Labs
18	University of California, Santa Cruz	USA	UCSC Green Labs
19	National Institute of Health	USA	NIH Green Labs Program
20	McGill University	USA	Sustainable Labs Guide
21	Princeton University	USA	Green Labs
22	The University of Queensland	AUS	Green Labs Program
23	The University of British Columbia	CAN	Green Labs
24	Massachusetts Institute of Technology	USA	MIT Green Labs

3.2 Actions found in university-based sustainability programs

The actions found in the 24 evaluated university-based sustainability programs were tabulated in a matrix (Figure 3.1) and classified into four categories. The numbers 1-24 of the university-based sustainability programs in the matrix (Figure 3.1) correspond to the university-based sustainability programs listed in Table 3.1. The symbol 'X' in the matrix indicates in which related subject area, actions towards more sustainable storage of samples at ultra-low temperatures could be found in each of the university-based sustainability programs. In addition, the frequency of found actions in all evaluated university-based sustainability programs in relation to each of the subject areas can be taken from the matrix, as well as the number of found actions in each of the evaluated university-based sustainability programs per category and in total.

Category	Action Nr.	related Code #	Related subject area	Description of related subject area	Frequency of actions found in all Green Lab Programs	Nr. of university-based sustainability program (Green Lab Program)																							
						1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
A "Green" Sample Management	1	A1	Inventory system	Clear, organized and up to date sample record system	15	x	x	x	x		x		x			x			x	x	x	x	x	x			x	x	
	2	A2	Sample clear-out	Removal of unused and unnecessary samples	20	x	x	x	x	x	x		x			x	x	x	x	x		x	x	x	x	x	x	x	x
	3	A3	Storage boxes and racks	Containers for organization and storage of sample vials	5	x	x		x	x	x																		
	4	A4	Sample vials	Containers for storage of samples	5						x								x			x	x				x		
	5	A5	Sample labeling	Labeling of stored sample vials	11		x		x	x	x					x	x		x	x			x	x				x	
	6	A6	Sample consolidation	Arrangement of samples at smallest possible footprint	7		x		x		x			x		x								x				x	
	7	A7	Storage temperature	Choice of sample storage temperature	12				x		x	x	x			x	x			x	x		x	x	x			x	
				Nr. of actions found in each Green Lab Program in Category A:		**3**	**5**	**2**	**6**	**3**	**7**	**1**	**3**	**1**	**0**	**5**	**3**	**1**	**4**	**4**	**2**	**3**	**5**	**5**	**2**	**1**	**3**	**5**	**1**
B "Green" Freezer Management	8	B1	ULT freezer manager	Person in charge for managing the ULT freezer	5	x			x		x		x															x	
	9	B2	ULT freezer location	Location where the ULT freezer is positioned	12	x	x	x	x	x	x		x							x	x	x		x			x		
	10	B3	Back-up ULT freezer setpoint	Choice of back-up ULT freezer temperature	4	x			x	x	x																		
	11	B4	ULT freezer setpoint	Choice of ULT freezer temperature	19	x	x	x	x	x	x	x	x	x		x	x	x				x	x	x		x	x	x	x
	12	B5	Airflow	Airflow around ULT freezer	8	x	x		x	x	x		x									x		x					
	13	B6	ULT freezer door closing	Proper closing of ULT freezer door	3		x	x		x																			
	14	B7	ULT freezer space	Management of ULT freezer inner space	8	x	x		x		x					x					x							x	x
	15	B8	Temperature monitoring	Monitoring and logging of ULT freezer inner temperature	7		x	x	x	x			x											x		x			
	16	B9	Energy monitoring	Monitoring ULT freezer energy usage	7		x	x	x		x		x									x					x		
	17	B10	ULT freezer alarm	Alarmsystem installed with ULT freezers in case of power-loss, break-down, failure or bad performance	6			x	x	x			x		x											x			
	18	B11	ULT freezer space sharing	Offering free ULT freezer space to others	15				x	x	x		x			x	x		x	x	x		x	x	x	x	x		x
	19	B12	Energy reduction device	Installation of energy reduction device to ULT freezer	1					x																			
	20	B13	Emergency instructions	Handling instructions in case of ULT freezer failure or	2					x			x																
	21	B14	ULT freezer consolidation	Combining contents of two ULT freezers in one ULT freezer	5											x	x				x					x			x
	22	B15	ULT freezer unplugging	Unplugging ULT freezers not in use	4												x				x			x		x			
				Nr. of actions in each Green Lab Program in Category B:		**6**	**7**	**6**	**10**	**10**	**8**	**1**	**9**	**1**	**1**	**4**	**4**	**1**	**1**	**2**	**5**	**4**	**2**	**6**	**1**	**6**	**4**	**3**	**4**
C Freezer Maintenance	23	C1	Preventive maintenance plan	Scheduling & arranging preventive maintenance	19	x	x		x	x	x		x	x	x	x		x	x	x	x	x		x	x	x	x	x	
	24	C2	ULT freezer frost removal	Removing of ice and defrosting of ULT freezer	22	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	
	25	C3	ULT freezer filters and vents care	Cleaning of filters and vents of ULT freezer	13	x	x	x	x	x	x		x		x	x						x		x		x	x		
	26	C4	ULT freezer seals care	Cleaning and replacement of ULT freezer seals	13	x	x	x	x		x	x	x				x			x		x		x		x	x		
	27	C5	ULT freezer heat exchange coils care	Cleaning of ULT freezer heat exchange coils	13				x	x	x		x	x		x	x	x				x		x	x	x	x		
				Nr. of actions in each Green Lab Program in Category C:		**4**	**4**	**3**	**5**	**4**	**5**	**2**	**5**	**3**	**3**	**4**	**2**	**3**	**2**	**3**	**2**	**5**	**1**	**5**	**3**	**5**	**5**	**2**	**0**
D "Green" Procurement Considerations	28	D1	Old ULT freezers	Replacing or removing old ULT freezers	14	x	x		x	x	x	x			x	x							x	x		x	x	x	x
	29	D2	Incentive program	Initiative towards replacement and rationalisation of ULT	15	x	x	x		x	x	x	x			x	x	x	x		x		x					x	x
	30	D3	Energy-efficient ULT freezers	Purchasing energy-efficient ULT freezers	22	x	x	x	x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x
	31	D4	Eco-Labels	Labels for ULT freezers and consumables that meet certain environmental management criteria	14				x		x	x	x			x		x	x			x	x	x	x	x	x	x	
				Nr. of actions in each Green Lab Program in Category D:		**3**	**3**	**2**	**3**	**3**	**4**	**4**	**3**	**0**	**1**	**4**	**2**	**3**	**3**	**1**	**2**	**2**	**4**	**3**	**2**	**3**	**3**	**4**	**3**
				Total Nr. of actions found in each Green Lab Program in all categories:		**16**	**19**	**13**	**24**	**20**	**24**	**8**	**20**	**5**	**5**	**17**	**11**	**8**	**10**	**10**	**11**	**14**	**12**	**19**	**8**	**15**	**15**	**14**	**8**

X…indicates in which subject area, measures, recommendations and considerations towards more sustainable storage of samples at ultra-low temperatures are

Figure 3.1 Matrix of actions in university-based sustainability programs

3.2.1 Number and percentage proportion of actions assigned to Categories A, B, C, D

As described in the Methods section, the found actions have been classified into four categories. Figure 3.2 shows the number and percentage proportion of actions in all four categories. Category A contains 7 (23%) actions related to sample management (related to e.g.: storage temperatures, storage containers, sample inventory systems). In comparison, almost half (15, 48%) of the actions towards more sustainable storage of samples at ultra-low temperatures are found in Category B including measures, recommendations and considerations related to the management of ULT freezers (related to e.g.: temperature setpoints, operation, location and monitoring of ULT freezers). The other 9 actions are distributed almost equally between Category C and D. Whereas Category C contains 5 (16%) actions related to ULT freezer maintenance topics, 4 (13%) actions are found in Category D related to purchasing considerations.

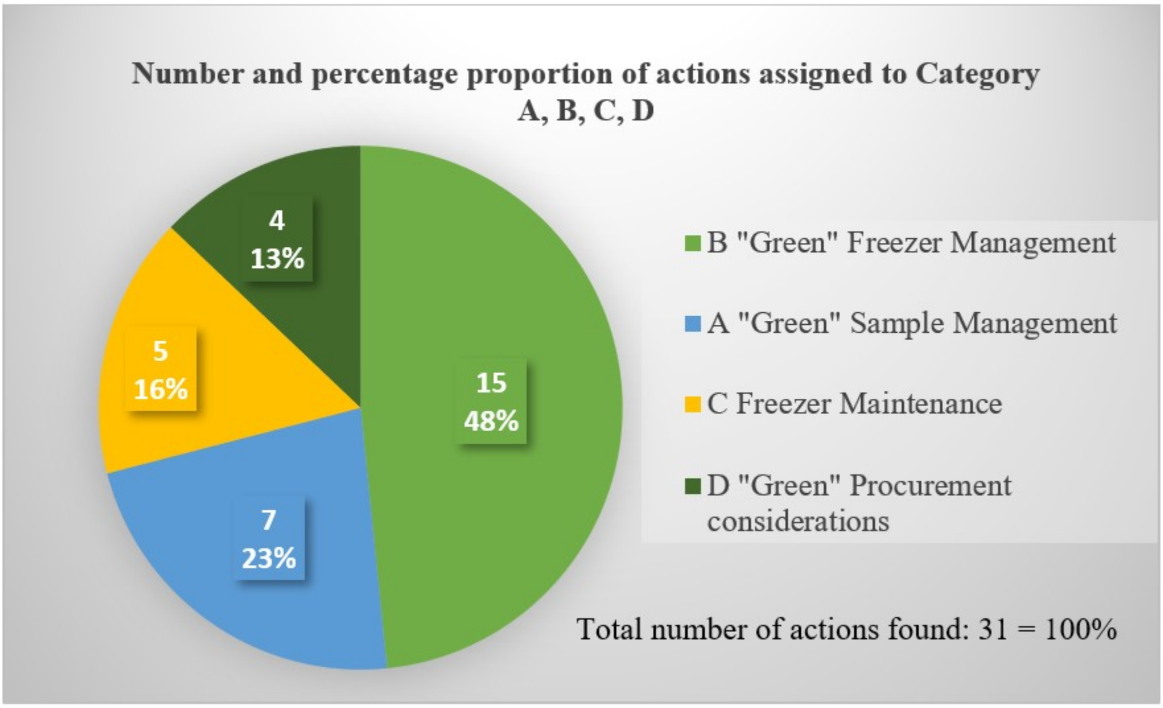


Figure 3.2 Number and percentage proportion of actions in Categories A, B, C, D

3.2.2 Description and frequency of actions assigned to Category A “Green” Sample Management

As described in the Methods section, the actions classified in Category A are related to measures, recommendations and considerations associated to sample management. In Table 3.2 all actions in Category A are described including their key statements.

Table 3.2 Description and key statements of actions in Category A "Green" Sample Management

Action Nr.	Related subject area	Description of action including key statements in Category A “Green” Sample Management
1.	A1: Inventory System	Keeping clear, good organized and up to date sample records in an inventory system helps to: • streamline handling processes • quicker access samples with knowing the location of the sample stored in the ULT freezer • reduce ‘open door’ times and therefore frost build up in the ULT freezer • reduce ‘open door’ times and therefore energy consumption to recover to initial ULT freezer setpoint temperature • reduce ‘open door’ times and therefore increasing freezer lifetime • only store samples that are necessary and therefore save freezer space
2.	A2: Sample clear-out	Maintaining a clear exit policy and removing unused and unnecessary samples from ULT freezers helps to: • free up ULT freezer space for new samples • reduce the need for additional ULT freezers and its energy consumption • consolidate samples from two ULT freezers in one ULT freezer

3.	A3: Storage boxes and racks	Keeping sample containers (sample vials) organized and stored in boxes and racks helps to: • keep cold air in the ULT freezer when the door is open and therefore, maintain a more constant temperature for samples • quicker retrieve samples and therefore reduce ‘open door’ time • save freezer space when appropriate boxes or racks for the type and size of sample containers (sample vials) are used • aid in the event of sample transfer in case of emergency or ULT freezer defrost
4.	A4: Sample vials	Maximizing sample container (sample vial) efficiency by choosing the minimal required sample vial size in a high-density format helps to: • increase the number of samples to be stored in a ULT freezer • save on plastic when choosing the smallest vial possible • not waste excessive ULT freezer space unnecessarily
5.	A5: Sample labeling	Samples should be labeled in a manner to identify the associated owner/laboratory, content, date of storage and expiry date/disposal date utilizing e.g. label markers, barcodes or an RFID (Radio Frequency Identification) system that withstand ultra-low temperatures. Ensuring clear identification of all stored samples through labeling helps to: • remove old, unnecessary or unused samples when not associated with active uses • quicker access samples and therefore reduce ‘open door’ time
6.	A6: Sample consolidation	Arranging samples at the smallest possible footprint, by arranging boxes/racks with samples to be mostly full, helps to:

		• efficiently use freezer space and increase the number of samples to be stored in a ULT freezer • reduce the need for purchasing additional ULT freezers and its energy consumption • offer any available space to others
7.	A7: Storage temperature	Considering storing only those samples that specifically need to be stored at ultra-low temperatures at -70°C/-80°C and elsewhere choosing appropriate (the highest possible) storage temperature for samples while ensuring effective preservation, helps to: • reduce the need for purchasing a ULT freezer and its energy consumption when considering room temperature sample storage (RTSS) for specific sample types like e.g. DNA, RNA • reduce the need of ULT freezers when considering -20°C storage temperature for specific sample types like e.g. DNA

The frequency of the 7 actions in the 24 evaluated university-based sustainability programs in Category A is shown in Figure 3.3. The most frequently found action is related to the subject area 'Sample clear-out' and was found in 20 university-based sustainability programs, promoting to maintaining a clear exit policy and removing unused and unnecessary samples in order to free up space and reduce the number of ULT freezers needed. This is followed by the action related to the subject area 'Inventory system', which was present in 15 university-based sustainability programs, indicating to keep clear, good organized and up to date sample records in an inventory system.

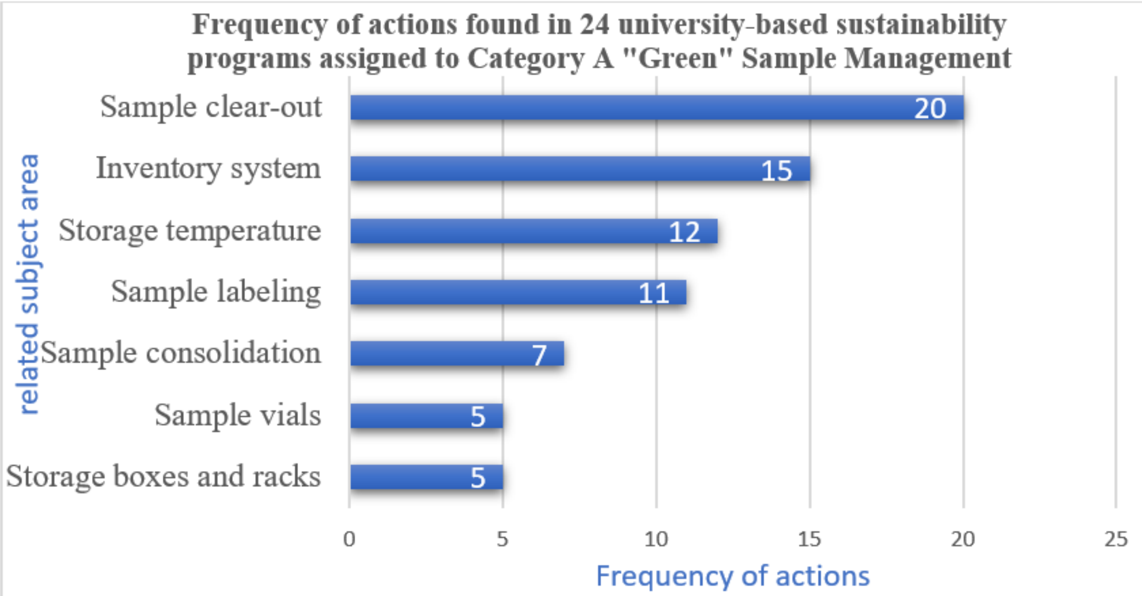


Figure 3.3 Frequency of actions in Category A "Green" Sample Management

3.2.3 Description and frequency of actions assigned to Category B "Green" Freezer Management

As described in the Methods section, the actions classified in Category B are related to measures, recommendations and considerations associated to freezer management. In Table 3.3 all actions in Category B are described including their key statements.

Table 3.3 Description and key statements of actions in Category B "Green" Freezer Management

Action Nr.	Related subject area	Description of action including key statements in Category B "Green" Freezer Management
8.	B1: ULT freezer manager	Nomination of a person in charge of managing ULT freezers helps to: • manage problems with the ULT freezer efficiently • manage general maintenance issues • improve sample management inside the ULT freezer • prevent that ULT freezers fall into bad condition
9.	B2: ULT freezer location	ULT freezers introduce additional heat load and therefore increase the ventilation and cooling loads in a facility. Selecting the best possible location under consideration of HVAC

		(heating, ventilation and air conditioning) conditions for ULT freezers being positioned helps to: • ensure the maximum energy efficiency of ULT freezers as ULT freezers work harder in a warm environment (preferably ambient temperature of 15°C to 22°C) • decrease energy consumption and costs for HVAC where facilities can cope with the additional heat load • decrease uncomfortable environment and risk of ULT freezer failures where facilities can not cope with the additional heat load • better monitor and regulate HVAC conditions when ULT freezers are placed in dedicated 'freezer farms', rather than offices or hallways
10.	B3: Back-up ULT freezer setpoint	Setting back-up ULT freezers to highest possible temperature still ensuring safety in the event of a ULT freezer failure helps to: • reduce energy consumption and running costs of a ULT back-up freezer, while ensuring to be cooled down to colder temperature in case of emergency (e.g. cooling down from -40°C or -60°C to -70°C)
11.	B4: ULT freezer setpoint	Raising ULT freezer temperatures by 5°C to 10°C, so-called 'Chill Up', from -80°C to -70°C, instead of setting to the lowest possible temperature, still ensuring sample stability and safety, helps to: • reduce the energy consumption of an individual ULT freezer by up to 20-40 % as well as reduce running costs (57,68,69) • prolong ULT freezer lifetime as compressors will have to work less and will therefore be preserved
12.	B5: Airflow	Ensuring proper airflow around ULT freezers to remove heat, by ensuring proper spacing, vents are not blocked and no items are around or on tops of the units, helps to: • avoid overheating of the ULT freezer (at least 150mm of space around, behind and above each ULT freezer)

		• ensure the maximum energy efficiency of ULT freezers as ULT freezers work harder in a warm environment • reduce risk of ULT freezer failure due to increased workload on compressors
13.	B6: ULT freezer door closing	Keeping ULT freezer doors shut and ensuring proper closing of inner and outer ULT freezer doors helps to: • prevent warm air entering the ULT freezer and therefore swift rise in temperature • reduces ice build-up in the ULT freezer
14.	B7: ULT freezer space	Managing of ULT freezer inner space by using a rack/shelf system helps to: • maximize ULT freezer capacity • efficiently use ULT freezer inner space • quickly transfer samples in the event of an emergency Avoiding large empty spaces by filling them up with polystyrene boxes/ice packs or filled water bottles (without overfilling to avoid wide temperature variations in the ULT freezer cabinet) helps to: • avoid warm air entering the ULT freezer cabinet • maintain ULT freezer temperature • ensure the maximum energy efficiency of the ULT freezer
15.	B8: Temperature monitoring	Monitoring and logging ULT freezer inner temperature with a secondary temperature probe helps to: • identify if ULT freezer does not reach its set point and compressor may run continually • direct concerns related to ULT freezer temperature to designated staff in order to manage problems in time • reduce the need to store samples at lower temperatures to have a 'buffer' that gives more time between a freezer breakdown and a threshold temperature being exceeded

16.	B9: Energy monitoring	Monitoring ULT freezer energy usage with a power meter device to assess the performance and efficiency of the freezer helps to: • understand how much energy is being used and is essential for developing a plan to improve energy efficiency • predict ULT freezer failure and preventative maintenance and reveal poor-performing ULT freezers • compare energy usage before and after replacement with a new unit to calculate the payback of investment
17.	B10: ULT freezer alarm	Ensuring an alarm system, with monitoring and logging, is installed with the ULT freezer in case of power-loss, breakdown, failure or bad performance helps to: • initiate an appropriate reaction to the alarm • avoid loss of samples • curb energy-wasting practices such as leaving doors open • reveal poor-performing ULT freezers
18.	B11: ULT freezer space sharing	Offering free ULT freezer space to others helps to: • reduce the number of ULT freezers needed in a department or institution • reduce overall energy consumption • resolve space problems • cover the need for ULT freezer space when defrosting or clearing out freezers • avoid buying a ULT freezer while, e.g. renting space in an existing unit • use ULT freezer space more efficiently
19.	B12: Energy reduction device	Installing an energy reduction device, like 'Savacontrol'(92) to ULT freezers helps to: • achieve energy savings

20.	B13: Emergency instructions	Availability of handling instructions in case of ULT freezer emergency, like failure or breakdown helps to: • initiate an appropriate reaction (e.g., activating back-up power supply, evacuating samples, etc.) • maintain ULT freezer inner temperature and protect samples • contact the person in charge to carry out the diagnosis and repair of the ULT freezer
21.	B14: ULT freezer consolidation	Combining contents of, e.g., two ULT freezers in one ULT freezer or of several ULT freezers running at low capacity, helps to: • reduce the number of ULT freezers plugged • reduce the number of ULT freezers needed, while offering empty space to others • efficiently use ULT freezer inner space • avoid large empty spaces in the ULT freezer and therefore ensure maximum energy efficiency
22.	B15: ULT freezer unplugging	Unplugging ULT freezers not in use or retired helps to: • reduce energy consumption

The frequency of the 15 actions found in the 24 evaluated university-based sustainability programs in Category B is shown in Figure 3.4. The most frequently found action is related to the subject area 'ULT freezer setpoint' and was found in 19 university-based sustainability programs, promoting to raise 'Chill Up' ULT freezer setpoint temperatures by 5°C to 10°C, from -80°C to -70°C, to reduce energy consumption and prolong lifetime of ULT freezers. This is followed by the action related to the subject area 'ULT freezer space sharing', which was found in 15 university-based sustainability programs.

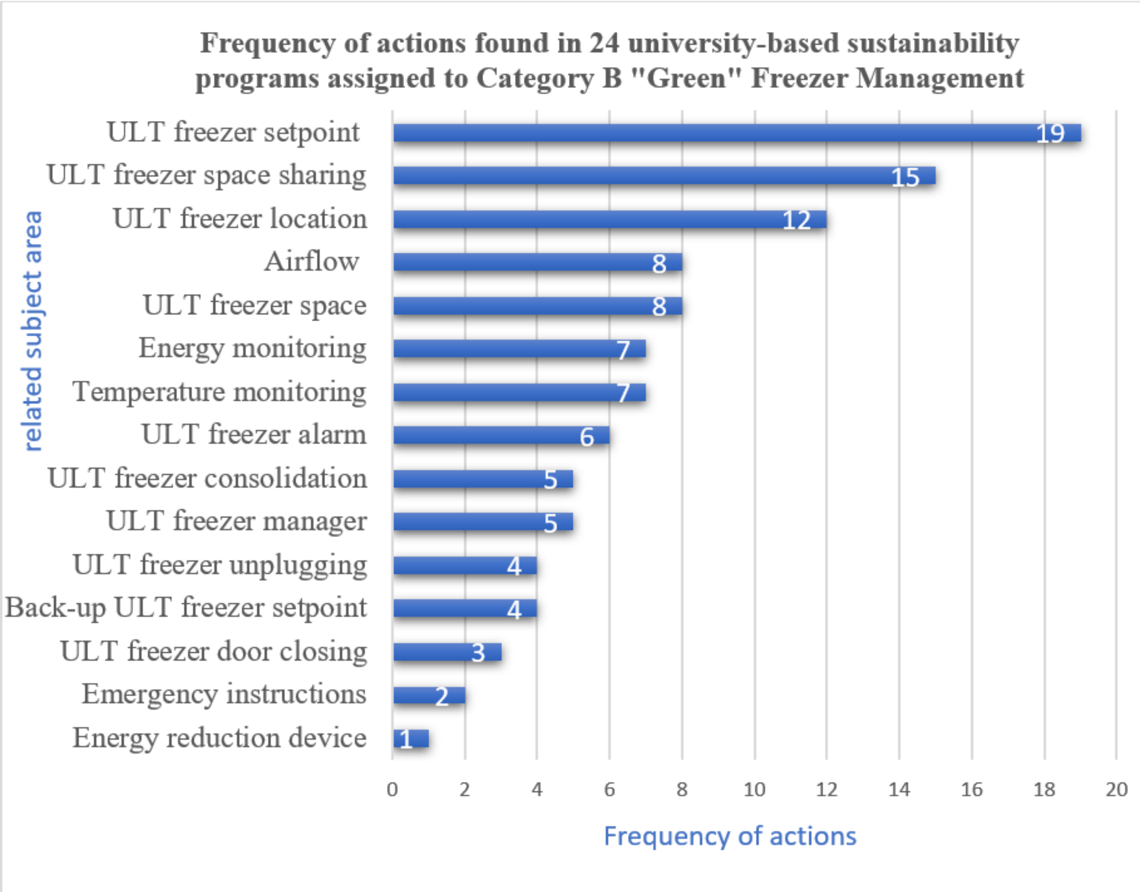


Figure 3.4 Frequency of actions in Category B "Green" Freezer Management

3.2.4 Description and frequency of actions assigned to Category C Freezer Maintenance

As described in the Methods section, the actions classified in Category C are related to measures, recommendations and considerations associated to ULT freezer maintenance. In Table 3.4 all actions in Category C are described including their key statements.

Table 3.4 Description and key statements of actions in Category C Freezer Maintenance

Action Nr.	Related subject area	Description of action including key statements in Category C Freezer Maintenance
23.	C1: Preventive maintenance plan	Scheduling and arranging regular (at least annually or as recommended by the manufacturer) preventive maintenance of ULT freezers helps to: • reduce the risk of ULT freezer failure or breakdown

		• prolong ULT freezer lifetime • ensure maximum energy efficiency of ULT freezers • ensure optimal performance (e.g., reach the setpoint temperature of the ULT freezer consistently)
24.	C2: ULT freezer frost removal	Removing of ice manually by scraping and defrosting of ULT freezers regularly helps to: • reduce frost build-up • reduce energy consumption, as ice build-up reduces heat exchange and forces compressors to work harder to maintain the setpoint temperature • maximize ULT freezer inner space as ice build-up reduces storage space • prolong ULT freezer lifetime
25.	C3: ULT freezer filters and vents care	Cleaning of filters and vents of ULT freezers regularly helps to: • reduce energy consumption as dirty/blocked filters and vents reduce the ability of ULT freezers to remove heat and force compressors to work harder to maintain the setpoint temperature • reduce the risk of ULT freezer failure or breakdown • prolong ULT freezer lifetime
26.	C4: ULT freezer seals care	Cleaning regularly and replacing damaged ULT freezer seals helps to: • reduce energy consumption as damaged seals or ice build-up allows air to enter the ULT freezer cabinet and compressors work harder to maintain the setpoint temperature • reduce the risk of ULT freezer failure or breakdown • prolong ULT freezer lifetime
27.	C5: ULT freezer heat exchange coils care	Cleaning/Vacuuming of ULT freezer heat exchange coils helps to:

		• reduce energy consumption as e.g., dirty/dusty coils on the outside of the ULT freezer inhibit effective heat removal • prolong ULT freezer lifetime

The frequency of the 5 found actions in the 24 evaluated university-based sustainability programs in Category C, related to Freezer Maintenance, is shown in Figure 3.5. The most frequently found action is related to the subject area 'ULT freezer frost removal' and was found in 22 university-based sustainability programs, promoting to regularly remove ice and defrost ULT freezers in order to reduce frost build-up, reduce energy consumption and prolong the lifetime of ULT freezers. This is followed by the action related to having a preventive maintenance plan in place, which was found in 19 university-based sustainability programs. Actions related to the care of ULT freezers seals, filters and vents as well as heat exchange coils were distributed equally and could be found in 13 university-based sustainability programs.

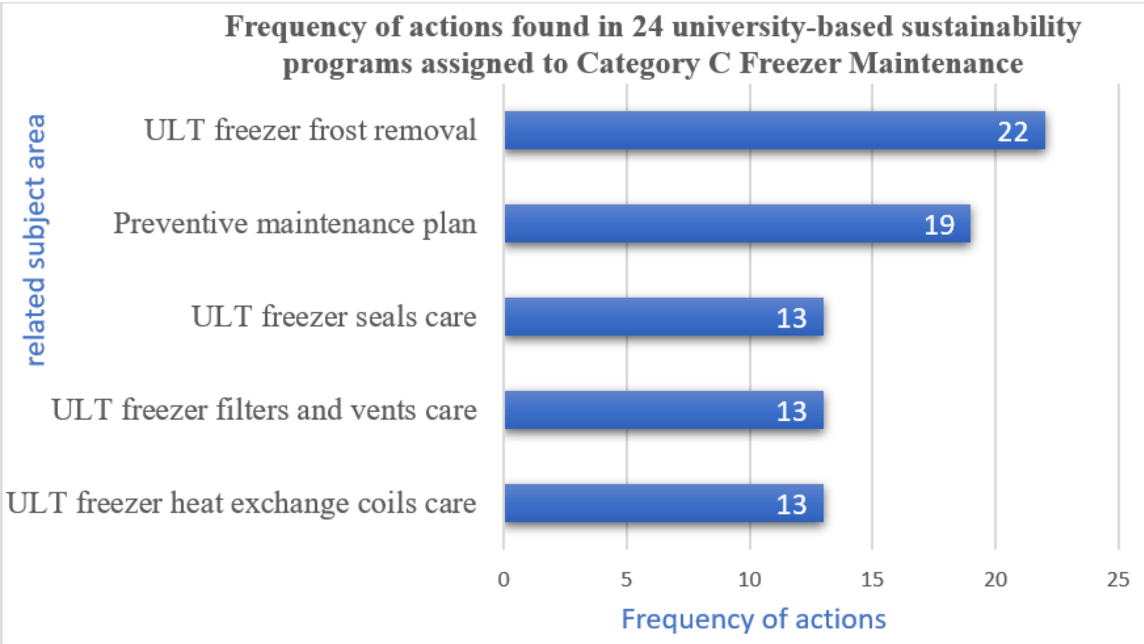


Figure 3.5 Frequency of actions in Category C Freezer Maintenance

3.2.5 Description and frequency of actions assigned to Category D "Green" Procurement Considerations

As described in the Methods section, the actions classified in Category D are related to measures, recommendations and considerations associated to procurement considerations. In Table 3.5 all actions in Category D are described including their key statements.

Table 3.5 Description and key statements of actions in Category D "Green" Procurement Considerations

Action Nr.	Related subject area	Description of action including key statements in Category D "Green" Procurement Considerations
28.	D1: Old ULT freezers	Considering replacement or retirement of old inefficient ULT freezers (>10 years) helps to: • reduce energy consumption with a newer and more energy-efficient ULT freezer model (older models can consume as much as e.g., 24 kWh/day compared to 9 kWh/day depending on model and size of the ULT freezer (69)). Further, the efficiency decreases over time due to wear and tear on the mechanical system, sealing, refrigerants, etc. • reduce costs for maintenance and repair • reduce the risk of ULT freezer failure or breakdown
29.	D2: Incentive program	An initiative towards replacement and/or rationalization of old ULT freezers offering financial subsidy and/or award helps to: • facilitate the procurement of energy-efficient ULT freezers by overcoming the cost barrier • create an incentive to retire and recycle old inefficient ULT freezers An initiative towards piloting room temperature sample storage offering financial subsidy helps to: • consider room temperature storage as an alternative storage conditions and therefore reduces the need for ULT freezers

30.	D3: Energy-efficient ULT freezers	Purchasing energy-efficient ULT freezers by considering: • energy consumption in kWh/day/liter or kWh/day/cubic feet, manufacturers often provide energy consumption data as kWh/day, in order to make comparisons possible, data must be normalized for volume • manufacturer's measuring method and testing conditions used to obtain energy figures, which vary in particular in relation to room temperature • considering long-term storage requirements and therefore the size of ULT freezers, as small ULT freezers with lower capacity consume more energy per liter/cubic feet than large ULT freezers with higher capacity • the balance between purchase costs and operation/maintenance as well as disposal costs (whole life-cycle costs) as part of the procurement decision, while an energy-efficient ULT freezer may have higher initial purchase costs, longer lifetime, lower energy and maintenance costs can compensate these costs • facility conditions (new facilities vs. old existing facilities) where process cooling with chilled water-loop system as well as reliable back-up power supply may exist and therefore e.g., water-cooled ULT freezers may be used • innovations in ULT freezer technologies and design helps to maximize energy efficiency of ULT freezers and reduce energy consumption.
31.	D4: Eco-Labels	Beside applying the 4-R hierarchy (Rethink, Reduce, Reuse, Recycle) before any new purchase and investigating whether there are more environmentally friendly options available, considering Eco-labels like:

		• 'Energy Star' Label from the U.S. Environmental Protection Agency (EPA) for laboratory-grade refrigerators and freezers • 'ACT' Environmental Impact Factor Label from My Green Lab for laboratory products (incl. consumables, chemicals and equipment) helps as a measure of sustainability when making a purchasing decision.

The frequency of the 4 actions found in the 24 evaluated university-based sustainability programs in Category D, related to "Green" Procurement Considerations, is shown in Figure 3.6. The most frequently found action is related to the purchasing of energy-efficient ULT freezers and was found in 22 university-based sustainability programs. This is followed by having an incentive program towards replacement and/or rationalization of old ULT freezers in place, which was found in 15 university-based sustainability programs. Replacement of old and inefficient ULT freezers as well as considering Eco-Labels when making purchasing decisions was found in 14 university-based sustainability programs.

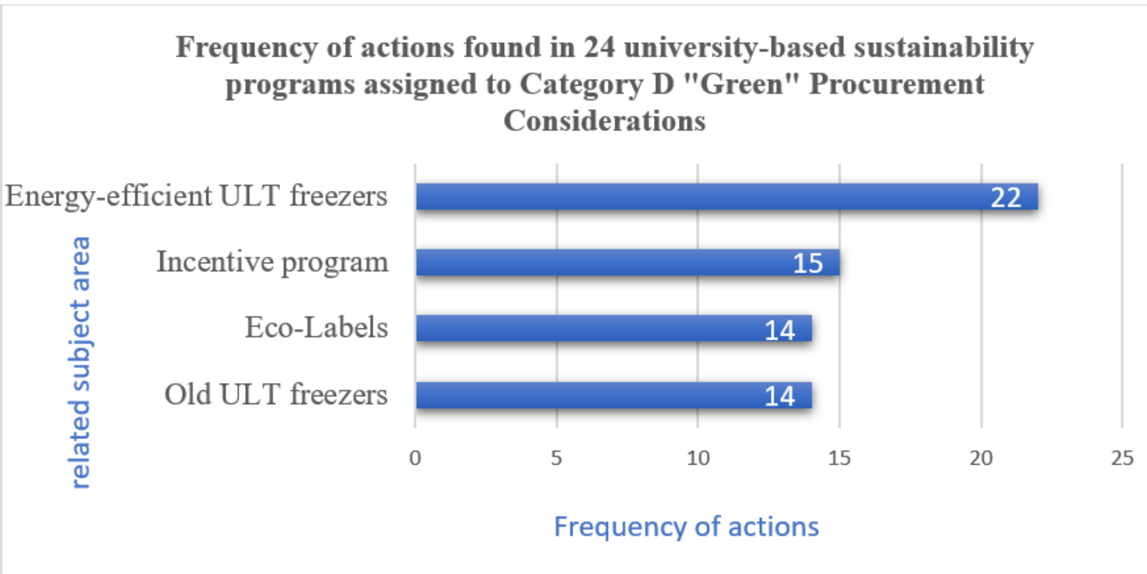


Figure 3.6 Frequency of actions in Category D "Green" Procurement Considerations

3.3 Comparison of actions found in university-based sustainability programs to ISBER Best Practices

Within the scope of this study, it was analyzed whether the subject areas and 31 actions towards more sustainable storage of samples at ultra-low temperatures found in the university-based sustainability programs are mentioned in the ISBER Best Practices - 4th Edition, 2018 (52). Further, as described in the Methods section, the level of correspondence of the ISBER Best Practices to the actions found in university-based sustainability programs was determined on three levels:

I. **Match** – when the principle of recommendations in ISBER Best Practices is substantially similar, identical or goes beyond the action promoted by university-based sustainability programs

II. **Context variation –** when the subject area is mentioned in ISBER Best Practices with variations in context and therefore does not directly correspond to the action promoted by university-based sustainability programs

III. **Not mentioned –** when neither the principle of action nor the related subject area is mentioned in ISBER Best Practices

Out of the 31 actions towards more sustainable storage of samples at ultra-low temperatures found in the evaluated university-based sustainability programs, 16 actions (52%) were mentioned in ISBER Best Practices and were assigned to the level of correspondence 'Match', five actions (16%) were assigned to the level of correspondence 'Context variation' where the related subject area is mentioned but with variations in the context. Ten actions (32%) were 'Not mentioned' in the ISBER Best Practices (Figure 3.7).

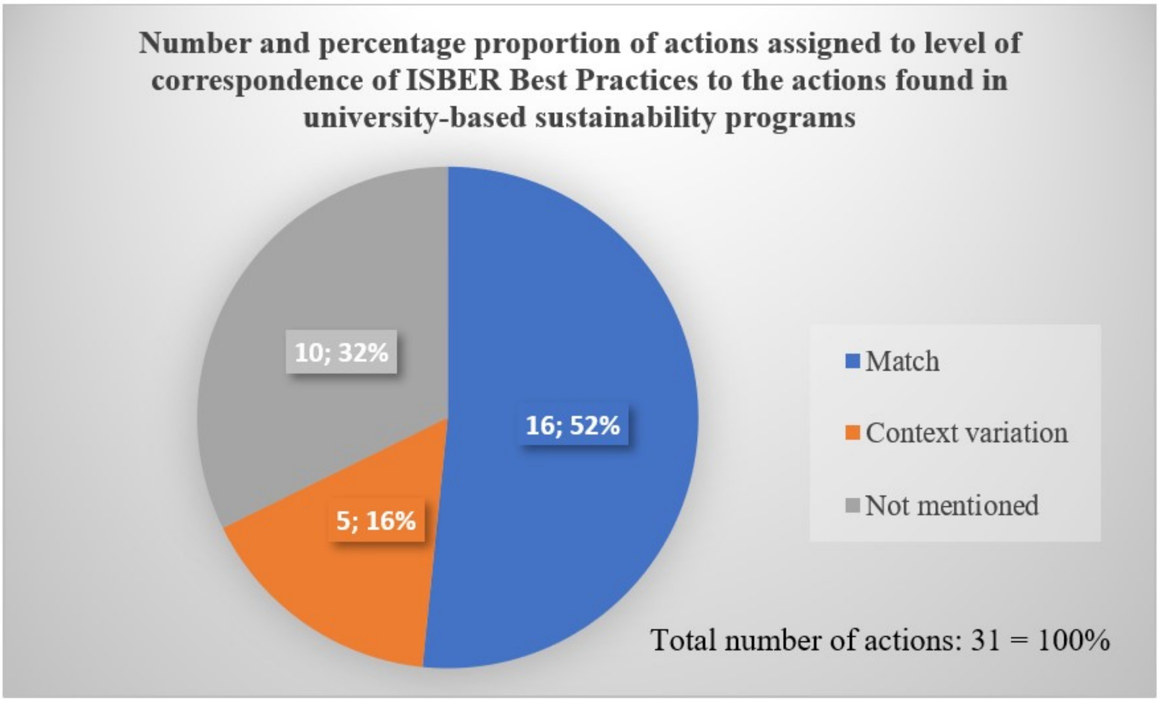


Figure 3.7 Number and percentage proportion of actions assigned to level of correspondence of ISBER Best Practices to the 31 actions found in university-based sustainability programs

3.3.1 Comparison of actions in Category A "Green" Sample Management found in university-based sustainability programs to ISBER Best Practices

All seven actions with their related subject areas in Category A, "Green" Sample Management, found in university-based sustainability programs are mentioned in ISBER Best Practices. Four actions (57%) could be assigned to the correspondence level 'Match' and three actions (43%) could be assigned to the correspondence level 'Context variation' (Table 3.6).

Table 3.6 Correspondence level of ISBER Best Practices to compared actions found in university-based sustainability programs in Category A

Action Nr.	Related subject area	Short Description of action found in university-based sustainability programs	ISBER Best Practices Level of correspondence
1	A1: Inventory system	Keeping clear, good organized and up to date sample records in an inventory system	x

2	A2: Sample clear-out	Maintaining a clear exit policy and removing unused and unnecessary samples from ULT freezers	**x**
3	A3: Storage boxes and racks	Keeping sample containers (sample vials) organized and stored in boxes and racks	**o**
4	A4: Sample vials	Maximizing sample container (sample vial) efficiency by choosing the minimal required sample vial size in a high-density format	**o**
5	A5: Sample labeling	Ensuring clear identification of all stored samples through labeling	**x**
6	A6: Sample consolidation	Arranging samples at the smallest possible footprint, by arranging boxes/racks with samples to be mostly full	**o**
7	A7: Storage temperature	Considering room temperature sample storage (RTSS)	**x**

x…indicates that the action found in university-based sustainability programs is mentioned in the ISBER Best Practices at the level **'Match'**

o…indicates that the action found in university-based sustainability programs is mentioned in the ISBER Best Practices at the level '**Context variation'**

\…indicates that the action found in university-based sustainability programs is **'Not mentioned'** in the ISBER Best Practices

Add Action Nr. 1 - Related subject area A1: Inventory System (Level of correspondence: Match)

In university-based sustainability programs, having an inventory system in place is described as an opportunity to reduce 'open door' time and streamline processes and therefore reduce energy consumption of ULT freezers. In ISBER Best Practices, having an inventory system in place is described as indispensable for effective and efficient sample management, supporting biospecimen utilization as well as being an integrative part of a Quality Management System in biobanks.

The ISBER Best Practices (52) recommend the development of a complete records management system enabling tracking of all biobank operations, including a computer-based inventory system for tracking of samples, including substantial events through the whole sample-lifecycle in a biobank. Components included in such inventory systems are the use of unique sample identifiers, appropriate sample labels, unique identification of sample storage location and record-keeping about the movement of storage location (e.g. building, room, freezer, rack, box, row, column) as well as record keeping about freezer type, location, and temperature. Further, the characteristics of samples including sample type and amount, vial type, date and time of sample collection, other relevant timestamps, methods of processing, storage temperatures, any information about samples being compromised, relevant study-data, should be included and tracked in the inventory system. Established SOPs (Standard Operating Procedures) and Quality Standards should be applied to ensure speed and efficiency when retrieving samples from storage (ISBER Best Practices, **Section D:** Quality Management - D5: Records Management; **Section I:** Repository Information Management System – I1: General, I2: Inventory System; **Section K:** Specimen Collection, Processing, Receiving and Retrieval – K8: Retrieval of Specimens from Storage).

Add Action Nr .2 - Related subject area A2: Sample clear-out (Level of correspondence: Match)

Maintaining a clear exit policy and removing unused and unnecessary samples is promoted as an action in university-based sustainability programs to free up storage space for new samples, reduce the need for additional storage capacities and its energy consumption and consolidating samples from e.g. two ULT freezers in one ULT freezer.

Similarly, the ISBER Best Practices (52) recommend having policies for the transfer or disposal of sample collections in place. The process of 'Culling' is described as periodically reviewing sample collections, determining the need for further storage and removing selected or even complete sample collections to combat limits in storage capacities and raising costs. Other reasons for the transfer or disposal of samples may be compromised sample quality, regulatory issues, or withdrawal of consent (ISBER Best Practices, **Section M:** Specimen Access, Utilization, and Disposition – M3: Specimen or Collection Disposition).

Add Action Nr. 3 - Related subject area A3: Storage boxes and racks (Level of correspondence: Mentioned in another context)

Keeping sample vials or containers organized and stored in boxes and racks is promoted in university-based sustainability programs as an action towards more sustainable storage of samples.

In the ISBER Best Practices (52), the subject of storage boxes and racks is mentioned in the context of inventory system record keeping and the variety of available configurations when choosing storage equipment (ISBER Best Practices, **Section I:** Repository Information Management System – I2.1: Specimen Location; **Section C:** Storage and Processing Equipment – C3: Mechanical Freezers, C4: Automated Storage Systems).

Add Action Nr. 4 - Related subject area A4: Sample vials (Level of correspondence: Mentioned in another context)

Maximizing sample vial efficiency by choosing the minimal required sample vial size in a high-density format is promoted as an action towards more sustainable storage of samples in university-based sustainability programs.

Considerations for choosing sample vials (sample containers) mentioned in the ISBER Best Practices (52) are given to long-term use, identification, contaminants, standardization, suitability to automation and new platforms (ISBER Best Practices, **Section K:** Specimen Collection, Processing, Receiving and Retrieval – K4: Collection and Storage Containers; **Section C:** Storage and Processing Equipment – C4: Automated Storage Systems).

Add Action Nr. 5 - Related subject area A5: Sample labeling (Level of correspondence: Match)

In university-based sustainability programs, sample labeling is promoted as an action to reduce 'open door' time and therefore energy consumption of ULT freezers and to support removing old, unnecessary or unused samples.

In ISBER Best Practices (52), sample labeling is described as indispensable for the accurate identification and tracking of samples in a biobank. It is recommended to have a unique human-readable identifier, electronically readable in form of e.g., barcode or Radio-Frequency Identification (RFID) for accurate identification and tracking of samples on each sample vial/container. Those identifiers have to be assessed for performance over a range of circumstances (e.g. readability and stability over time at various conditions) as well as compatibility to downstream processes (e.g. automation) before use. In contrast, handwritten labeling is explicitly not recommended (ISBER Best Practices, **Section C:** Storage and Processing Equipment – C1.2: Identification of Specimen Storage Containers; **Section I:** Repository Information Management System – I2.13: Labels).

Add Action Nr. 6 - Related subject area A6: Sample consolidation (Level of correspondence: Mentioned in another context)

Sample consolidation is promoted in university-based sustainability programs to efficiently use ULT freezer space and reduce the need for additional ULT freezers and energy consumption.

In contrast, ISBER Best Practices (52) mention sample consolidation in the context of considerations for an automated storage system capable of 'defragmentation', consolidating empty positions of stored racks, as an opportunity to maximize storage capacity (ISBER Best Practices, **Section C:** Storage and Processing Equipment – C4: Automated Storage Systems).

Add Action Nr. 7 - Related subject area A7: Storage temperature (Level of correspondence: Match)

In university-based sustainability programs, considerations of the choice of sample storage temperature (highest possible storage temperature) as an opportunity towards more sustainable sample storage can be found. Especially Room Temperature Samples Storage (RTSS) is promoted as an energy-saving storage solution.

The ISBER Best Practices (52) recommend to carefully consider and document collection, process and storage temperature while taking the impact of temperature on sample integrity as well as intended future analysis and duration of storage into consideration when choosing sample storage temperature. Room Temperature Samples Storage (RTSS) is mentioned as an energy-saving storage solution or when cold storage equipment is not available, for sample types including dry blood spots, isolated RNA/DNA or even more complex sample types (ISBER Best Practices, **Section C:** Storage and Processing Equipment – C7: Ambient Temperature Storage; **Sektion K:** Specimen Collection, Processing, Receiving and Retrieval – K3: Specimen Integrity).

3.3.2 Comparison of actions in Category B "Green" Freezer Management found in university-based sustainability programs to ISBER Best Practices

Out of the 15 actions with their related subject areas in Category B, "Green" Freezer Management, found in university-based sustainability programs, seven actions (47%) were assigned to the level of correspondence 'Match', two actions (13%) were assigned to the level of correspondence 'Context Variation' and six actions (40%) were assigned to the level of correspondence 'Not mentioned' (Table 3.7).

Table 3.7 Correspondence level of ISBER Best Practices to compared actions found in university-based sustainability programs in Category B

Action Nr.	Related subject area	Short Description of action found in university-based sustainability programs	ISBER Best Practices Level of correspondence
8	B1: ULT freezer manager	Nomination of a person in charge of managing ULT freezers	**x**
9	B2: ULT freezer location	Selecting the best possible location for ULT freezers under consideration of HVAC (heating, ventilation and air conditioning) conditions	**x**
10	B3: Back-up ULT freezer setpoint	Setting back-up ULT freezers to highest possible temperature still ensuring safety in the event of a ULT freezer failure	**o**
11	B4: ULT freezer setpoint	Raising ULT freezer temperatures 'Chill Up', from -80°C to -70°C	\
12	B5: Airflow	Ensuring proper airflow around ULT freezers to remove heat	**x**
13	B6: ULT freezer door closing	Keeping ULT freezer doors shut and ensuring proper closing of inner and outer ULT freezer doors	**x**

14	B7: ULT freezer space	Managing of ULT freezer inner space by using a rack/shelf system and avoiding large empty spaces by filling them up	**o**
15	B8: Temperature monitoring	Monitoring and logging ULT freezer inner temperature with a secondary temperature probe	**x**
16	B9: Energy monitoring	Monitoring ULT freezer energy usage with a power meter device	\
17	B10: ULT freezer alarm	Ensuring an alarm system, with monitoring and logging, is installed with ULT freezers in case of power-loss, breakdown, failure or bad performance	**x**
18	B11: ULT freezer space sharing	Offering free ULT freezer space to others	\
19	B12: Energy reduction device	Installation of energy reduction device to ULT freezers	\
20	B13: Emergency instructions	Availability of handling instructions in case of ULT freezer emergency, like failure or breakdown	**x**
21	B14: ULT freezer consolidation	Combining contents of, e.g., two ULT freezers in one ULT or of several ULT freezers running at low capacity	\
22	B15: ULT freezer unplugging	Unplugging ULT freezers not in use or retired	\

x…indicates that the action found in university-based sustainability programs is mentioned in the ISBER Best Practices at the level **'Match'**

o…indicates that the action found in university-based sustainability programs is mentioned in the ISBER Best Practices at the level **'Context variation'**

\…indicates that the action found in university-based sustainability programs is **'Not mentioned'** in the ISBER Best Practices

Add Action Nr. 8 - Related subject area B1: ULT freezer manager (Level of correspondence: Match)

University-based sustainability programs promote the nomination of a person in charge of managing ULT freezers, a so-called 'ULT freezer manager', to efficiently manage ULT freezer problems, maintenance issues and improve sample management.

The ISBER Best Practices (52) recommend having an organizational structure with clear descriptions of tasks to be carried out by each position in a biobank and employees have to be suitably trained to carry out the required tasks. The activities carried out by the technical staff of a biobank can include the management of equipment (e.g. ULT Freezers) and facilities, among other things like sample collection, processing, quality control, sample dispatch, receipt and storage or data management (ISBER Best Practices, **Section A:** Planning Considerations **-** A5: Repository Personnel).

Add Action Nr. 9 - Related subject area B2: ULT freezer location (Level of correspondence: Match)

University-based sustainability programs promote selecting the best possible location under consideration of HVAC (heating, ventilation and air conditioning) conditions for ULT freezers being positioned to ensure maximum energy efficiency of ULT freezers, decrease energy consumption and costs for HVAC, decrease uncomfortable environment as well as risk of ULT freezer failures. Having ULT freezers placed in dedicated 'freezer farms' rather than offices or hallways allows better monitoring and regulation of HVAC conditions.

The ISBER Best Practices (52) recommend positioning freezers in biobanks in such a way as to ensure sufficient air conditioning and airflow to prevent additional stress on the mechanical freezers and their compressor systems to prevent overheating, wear out and failure. Ambient temperatures should be monitored and controlled according to the information provided by the manufacturer. ISBER Best Practices mention HVAC systems being more efficient in maintaining both temperature and humidity compared to simple ventilation systems (ISBER Best Practices, **Section B:** Facilities **-** B2: Heating, Ventilation, and Air Conditioning; **Section C:** Storage and Processing Equipment - C3: Mechanical Freezers).

Add Action Nr. 10 - Related subject area B3: Back-up ULT freezer setpoint (Level of correspondence: Mentioned in another context)

Setting back-up ULT freezers to highest possible temperature still ensuring safety in the event of a ULT freezer failure is promoted in university-based sustainability programs to reduce energy consumption and running costs of a ULT back-up freezer.

In contrast, ISBER Best Practices (52) mention having back-up equipment kept at operating temperature, whereas it is not clear if the operating temperature is meant to be equal to the ULT freezer setpoint for specific storage conditions (ISBER Best Practices, **Section C:** Storage and Processing Equipment – C9: Backup Storage Capacity).

Add Action Nr. 11 - Related subject area B4: ULT freezer setpoint (Level of correspondence: Not mentioned)

University-based sustainability programs promote 'Chilling Up' ULT freezers by raising the setpoint temperatures by 5°C to 10°C, from -80°C to -70°C, instead of setting to the lowest possible temperature in order to reduce the energy consumption, operating costs and prolong ULT freezer lifetime.

The ISBER Best Practices (52) recommend making every effort to reduce the costs for the operation of equipment due to continuously increasing costs for the maintenance of biobanks. However, the measure mentioned above, as well as the related subject area, is not explicitly mentioned.

Add Action Nr. 12 - Related subject area B5: Airflow (Level of correspondence: Match)

University-based sustainability programs promote ensuring proper airflow around ULT freezers to remove heat by ensuring proper spacing, vents are not blocked, and no items are around or on tops of the units to avoid overheating, maximize energy efficiency and reduce the risk of failure of ULT freezers.

ISBER Best Practices (52) also recommend ensuring sufficient airflow, taking into account appropriate distances between freezers and between freezers and walls, to prevent compressor overheating and extend compressor life. Further prevention of mold and other harmful microbial contamination is mentioned in the context of adequate airflow (ISBER Best Practices, **Section C:** Storage and Processing Equipment - C3: Mechanical Freezers).

Add Action Nr. 13 - Related subject area B6: ULT freezer door closing (Level of correspondence: Match)

University-based sustainability programs promote keeping ULT freezer doors shut and ensuring proper closing of inner and outer ULT freezer doors to prevent warm air entering the ULT freezer and to reduce ice build-up in the ULT freezer.

The ISBER Best Practices (52) go beyond this and recommend that freezers and other storage equipment be individually locked and a system be set up that restricts access to the storage equipment to persons who are entrusted with biobank operations and keeping records of access (ISBER Best Practices, **Section B:** Facilities **-** B6: Security and Access).

Add Action Nr. 14 - Related subject area B7: ULT freezer space (Level of correspondence: Mentioned in another context)

University-based sustainability programs promote managing ULT freezer inner space by using a rack/shelf system to maximize capacity and efficiently use ULT freezer inner space. Avoiding large empty spaces by filling them up with polystyrene boxes/ice packs or filled water bottles is also recommended to avoid warm air entering the ULT freezer cabinet and ensure the maximum energy efficiency of ULT freezers.

In contrast, in the ISBER Best Practices (52), the subject of ULT freezer space and using a rack/shelf system is mentioned in the context of inventory system record keeping having a system for numbering shelves, racks and boxes established (ISBER Best Practices, **Section I:** Repository Information Management System – I2.1: Specimen Location).

Add Action Nr. 15 - Related subject area B8: Temperature monitoring (Level of correspondence: Match)

University-based sustainability programs promote monitoring and logging ULT freezer inner temperature with a secondary temperature probe to identify if a ULT freezer does not reach its set point, direct concerns related to ULT freezers to designated staff. Further, it is mentioned as an opportunity to reduce the need to store biospecimens at lower temperatures to have a 'buffer' that gives more time between a freezer breakdown and a threshold temperature being exceeded.

Similarly, the ISBER Best Practices (52) recommend monitoring and logging ULT freezer inner temperature (temperature mapping) to ensure that samples are stored within the specified temperature range and to locate areas of most significant temperature variations as well as differences, analyze the causes and check that the storage system maintains the correct temperature in all situations. It is recommended to review and document temperature mapping at regular, defined intervals (ISBER Best Practices, **Section C:** Storage and Processing Equipment – C1: General).

Add Action Nr. 16 - Related subject area B9: Energy monitoring (Level of correspondence: Not mentioned)

University-based sustainability programs promote monitoring ULT freezer energy usage with a power meter device to assess the performance and efficiency of the freezer in order to understand how much energy is being used, predict ULT freezer failure and preventative maintenance and reveal poor-performing ULT freezers.

The ISBER Best Practices (52) recommend having a system for routine assessment of storage equipment in place. However, the measure mentioned above, as well as the related subject area, is not explicitly mentioned.

Add Action Nr. 17 - Related subject area B10: ULT freezer alarm (Level of correspondence: Match)

University-based sustainability programs promote to ensure an alarm system, with monitoring and logging, is installed with ULT freezers in case of power-loss, breakdown, failure or bad performance in order to initiate appropriate reactions to alarms, avoid loss of biospecimens, curb energy-wasting practices such as leaving doors open and reveal poor-performing ULT freezers.

In comparison, ISBER Best Practices (52) go beyond, besides regular temperature monitoring by biobank staff, a safety system and an automatic temperature monitoring system is recommended. In addition to acoustic alarms, these systems should inform the responsible staff actively and around the clock whenever an alarm is triggered. It is also recommended that the logged temperature data of the storage equipment is checked to assess performance and determine the need for maintenance (ISBER Best Practices, **Section B:** Facilities **-** B6.1: Security Systems).

Add Action Nr. 18 - Related subject area B11: ULT freezer space sharing (Level of correspondence: Not mentioned)

University-based sustainability programs promote offering free ULT freezer space to others in order to reduce the number of ULT freezers needed in a department or institution, reduce

overall energy consumption, resolve space problems, avoid buying additional ULT freezers and use ULT freezer space more efficiently.
Although ISBER Best Practices (52) mention that biobanks, in general may be set up for an individual organization as well as to serve other organizations, the measure mentioned above, as well as the related subject area, is not explicitly mentioned.

Add Action Nr. 19 - Related subject area B12: Energy reduction device (Level of correspondence: Not mentioned)

Installing an energy reduction device to ULT freezers to achieve energy savings was mentioned in one university-based sustainability program.
The ISBER Best Practices (52) recommend making every effort to reduce the costs for the operation of equipment due to continuously increasing costs for the maintenance of biobanks. However, the measure mentioned above is not explicitly mentioned.

Add Action Nr. 20 - Related subject area B13: Emergency instructions (Level of correspondence: Match)

University-based sustainability programs promote having handling instructions in place in case of ULT freezer emergencies to initiate the appropriate actions in order to maintain ULT freezer inner temperature and protect biospecimens.
The ISBER Best Practices (52) recommend having an emergency plan with a checklist in place so that the responsible biobank staff can follow procedures to safeguard sample collections and the ability of the biobank to continue to perform crucial functions in an emergency. The recommendations even go beyond this by mentioning that biobanks may consider splitting up precious and irreplaceable sample collections and storing them in separate geographical locations (ISBER Best Practices, **Section B:** Facilities **-** B8.1: Emergency Response Planning).

Add Action Nr. 21 - Related subject area B14: ULT freezer consolidation (Level of correspondence: Not mentioned)

University-based sustainability programs promote combining the contents of two ULT freezers in one ULT or of several ULT freezers running at low capacity in order to reduce the number of ULT freezers plugged as well as to reduce the number of ULT freezers needed.
The ISBER Best Practices (52) recommend making every effort to reduce the costs for the operation of equipment due to continuously increasing costs for the maintenance of

biobanks. However, the measure mentioned above, as well as the related subject area, is not explicitly mentioned.

Add Action Nr. 22 - Related subject area B15: ULT freezer unplugging (Level of correspondence: Not mentioned)

University-based sustainability programs promote unplugging ULT freezers not in use or retired in order to reduce energy consumption.

The ISBER Best Practices (52) recommend making every effort to reduce the costs for the operation of equipment due to continuously increasing costs for the maintenance of biobanks. However, the measure mentioned above is not explicitly mentioned.

3.3.3 Comparison of actions in Category C Freezer Maintenance found in university-based sustainability programs to ISBER Best Practices

Out of the five actions with their related subject areas in Category C, Freezer Maintenance, found in university-based sustainability programs, three actions (60%) were mentioned in ISBER Best Practices and could be assigned to the correspondence level ‘Match’, whereas two actions (40%) were not mentioned (Table 3.8).

Table 3.8 Correspondence level of ISBER Best Practices to compared actions found in university-based sustainability programs in Category C

Action Nr.	Related subject area	Short Description of action found in university-based sustainability programs	ISBER Best Practices Level of correspondence
23	C1: Preventive maintenance plan	Scheduling and arranging regular preventive maintenance of ULT freezers	x
24	C2: ULT freezer frost removal	Removing of ice and defrosting of ULT freezer	x
25	C3: ULT freezer filters and vents care	Cleaning of filters and vents of ULT freezer	x
26	C4: ULT freezer seals care	Cleaning and replacement of ULT freezer seals	\
27	C5: ULT freezer heat exchange coils care	Cleaning of ULT freezer heat exchange coils	\

x…indicates that the action found in university-based sustainability programs is mentioned in the ISBER Best Practices at the level **'Match'**
o…indicates that the action found in university-based sustainability programs is mentioned in the ISBER Best Practices at the level **'Context variation'**
\…indicates that the action found in university-based sustainability programs is **'Not mentioned'** in the ISBER Best Practices

Add Action Nr. 23 - Related subject area C1: Preventive maintenance plan (Level of correspondence: Match)

University-based sustainability programs promote scheduling and arranging regular preventive maintenance of ULT freezers to reduce the risk of ULT freezer failure or breakdown, prolong ULT freezer lifetime and ensure maximum energy efficiency and optimal performance of ULT freezers.

ISBER Best Practices (52) also recommend to have a system for regular preventive maintenance as well as routine assessment of storage equipment in place, taking into account the manufacturer's recommendations, in order to prolong the equipment´s lifetime (ISBER Best Practices, **Section C:** Storage and Processing Equipment – C12: Equipment Maintenance, Repair, and Replacement).

Add Action Nr. 24 - Related subject area C2: ULT freezer frost removal (Level of correspondence: Match)

University-based sustainability programs promote removing ice manually by scraping and defrosting of ULT freezers regularly to reduce frost build-up, reduce energy consumption, maximize ULT freezer inner space and prolong ULT freezer lifetime.

The ISBER Best Practices (52) recommend to determine and perform routine assessment and adjustment of storage equipment according to the manufacturer's recommendations, what may include regular manual removal of ice from the interior of freezers to extend the lifetime of the equipment (ISBER Best Practices, **Section C:** Storage and Processing Equipment – C12.3: Equipment Preventative Maintenance and Repair).

Add Action Nr. 25 - Related subject area C3: ULT freezer filters and vents care (Level of correspondence: Match)

University-based sustainability programs promote cleaning filters and vents of ULT freezers regularly to reduce energy consumption, reduce the risk of ULT freezer failure or breakdown and prolong ULT freezer lifetime.

The ISBER Best Practices (52) recommend determining and perform routine assessment and adjustment of storage equipment according to the manufacturer's recommendations, what may include regular cleaning of freezer filters to extend the lifetime of the equipment (ISBER Best Practices, **Section C:** Storage and Processing Equipment – C12.3: Equipment Preventative Maintenance and Repair).

Add Action Nr. 26 - Related subject area C4: ULT freezer seals care (Level of correspondence: Not mentioned)

University-based sustainability programs promote to regularly clean and replace damaged ULT freezer seals to reduce energy consumption, reduce the risk of ULT freezer failure or breakdown and to prolong ULT freezer lifetime.

The ISBER Best Practices (52) recommend to determine and perform routine assessment and adjustment of storage equipment according to the manufacturer's recommendations. However, the measure mentioned above, as well as the related subject area, is not explicitly mentioned.

Add Action Nr. 27 - Related subject area C5: ULT freezer heat exchange coils care (Level of correspondence: Not mentioned)

University-based sustainability programs promote cleaning/vacuuming of ULT freezer heat exchange coils to reduce energy consumption and prolong ULT freezer lifetime.

The ISBER Best Practices (52) recommend to determine and perform routine assessment and adjustment of storage equipment according to the manufacturer's recommendations. However, the measure mentioned above, as well as the related subject area, is not explicitly mentioned.

3.3.4 Comparison of actions in Category D "Green" Procurement Considerations found in university-based sustainability programs to ISBER Best Practices

Out of the four actions with its related subject areas in Category D, “Green” Procurement Considerations, found in university-based sustainability programs, two actions (50%) were mentioned in ISBER Best Practices and could be assigned to the correspondence level ‘Match’, whereas two actions (50%) were not mentioned (Table 3.9).

Table 3.9 Correspondence level of ISBER Best Practices to compared actions found in university-based sustainability programs in Category D

Action Nr.	Related subject area	Short Description of action found in university-based sustainability programs	ISBER Best Practices Level of correspondence
28	D1: Old ULT freezers	Considering replacement or retirement of old inefficient ULT freezers	**x**
29	D2: Incentive program	Having an initiative towards replacement and/or rationalization of old ULT freezers offering financial subsidy and/or award in place	\
30	D3: Energy-efficient ULT freezers	Purchasing energy-efficient ULT freezers	**x**
31	D4: Eco-Labels	Considering Eco-labels as a measure of sustainability when making a purchasing decision	\

x…indicates that the action found in university-based sustainability programs is mentioned in the ISBER Best Practices at the level **‘Match’**

o…indicates that the action found in university-based sustainability programs is mentioned in the ISBER Best Practices at the level **‘Context variation’**

\…indicates that the action found in university-based sustainability programs is **‘Not mentioned’** in the ISBER Best Practices

Add Action Nr. 28 - Related subject area D1: Old ULT freezers (Level of correspondence: Match)

University-based sustainability programs promote considering replacement or retirement of old inefficient ULT freezers (>10 years) to reduce energy consumption, reduce costs for maintenance and repair and to reduce the risk of ULT freezer failure or breakdown.

ISBER Best Practices (52) recommend having a long-term plan that takes into account both the repair and replacement of storage equipment, taking into account the expected lifetime according to the manufacturer as well as the different actual lifespans, in order to ensure the continued operation of a biobank, whereby the cost of necessary repairs may lead to the decision to replace a device (ISBER Best Practices, **Section C:** Storage and Processing Equipment – C12.4: Repair vs. Replacement).

Add Action Nr. 29 - Related subject area D2: Incentive program (Level of correspondence: Not mentioned)

University-based sustainability programs offer incentive programs, as an initiative towards replacement and rationalization of old ULT freezers offering financial subsidy or award to facilitate the procurement of energy-efficient ULT freezers and to create an incentive to retire and recycle old inefficient ULT freezers. Some of those programs also cover room temperature sample storage, offering a financial subsidy to consider room temperature storage as an alternative storage condition and therefore reduces the need for ULT freezers.

The measure mentioned above, as well as the related subject area, is not explicitly mentioned in the ISBER Best Practices (52).

Add Action Nr. 30 - Related subject area D3: Energy-efficient ULT freezers (Level of correspondence: Match)

University-based sustainability programs promote purchasing energy-efficient ULT freezers by considering the energy consumption, manufacturer's measuring method and testing conditions used to obtain energy figures, long-term storage requirements, the balance between purchase costs and operation/maintenance as well as disposal costs (whole life-cycle costs), facility conditions and innovations in ULT freezer technologies and design.

The ISBER Best Practices (52) recommend to find the most energy-efficient devices that meet the requirements before each purchase in order to keep the costs of operating a biobank as low as possible. New developments are mentioned, such as freezers with free-piston technology, which consume less energy than compressor-based systems. Furthermore, it is mentioned that freezers using water-cooled compressor systems or where the condensers can be placed on the outside of the building can counteract high loads (through the release of heat) on HVAC Systems (heating, ventilation and air conditioning), thus offering energy and cost-saving potential. As a further aspect, the availability of equipment that uses LN2 as a coolant for storage temperatures from +4°C to -80°C is also mentioned, offering the benefit of being able to maintain the temperature when facing a power malfunction. In addition, ISBER Best Practices (52) mention that most cascade freezer systems, walk-in freezers and automated storage systems usually require a smaller footprint, lower HVAC output and lower energy consumption compared to individual stand-alone mechanical freezers. Although the initial investment costs are usually higher than for individual stand-alone mechanical freezers, they can be worthwhile in the long run (ISBER Best Practices, **Section C:** Storage and Processing Equipment – C1: General, C3: Mechanical Freezers, C4: Automated Storage Systems, C6: Walk-In Environmental Storage Systems).

Add Action Nr. 31 - Related subject area D4: Eco-Labels (Level of correspondence: Not mentioned)

University-based sustainability programs promote to investigate whether there are more environmentally friendly options available, considering Eco-labels like the Energy Star" Label or the 'ACT' Environmental Impact Factor Label. The ISBER Best Practices (52) recommend to find the most energy-efficient devices that meet the requirements before each purchase in order to keep the costs of operating a biobank as low as possible. However, the measure mentioned above, as well as the related subject area, is not explicitly mentioned.

4 Discussion

In this section, the results from the evaluation of the university-based sustainability programs, as well as the comparison of the found actions towards more sustainable storage of samples at ultra-low temperatures to ISBER Best Practices, presented in section 3, are discussed. Subsequently, a conclusion of this thesis is drawn and an outlook into further needed research is given.

4.1 Discussion of the evaluation of university-based sustainability programs

Based on the analysis of 24 university-based sustainability programs, 31 actions in form of measures, recommendations and considerations towards more sustainable storage of samples at ultra-low temperatures could be found within the topics of sample management, freezer management, freezer maintenance and procurement considerations. The majority of the university-based sustainability programs found and selected for evaluation in this study are in the United States. In contrast, in Europe, the UK is playing the leading role in laboratory sustainability with its Laboratory Efficiency Assessment Framework (LEAF) (32).

The most frequently found actions towards more sustainable storage of samples at ultra-low temperatures include actions related to reduce the energy consumption of ULT freezers including purchasing energy-efficient ULT freezers that meet certain criteria, like holding an Energy Star label (93), which is relatively new to ULT freezers.

Therefore, incentive programs with financial subsidies are facilitating the retirement and recycling of old inefficient freezers and facilitate the procurement of energy-efficient ULT freezers by overcoming the cost barrier. Further, scheduling and arranging preventive ULT freezer maintenance including defrosting, removing of ice, cleaning of filters, vents, seals and heat exchange coils are promoted to reduce energy consumption, reduce the risk of ULT freezer failure or breakdown and prolong its lifetime. This is followed by the behaviour change movement to ‘Chill Up’ ULT freezers by raising the setpoint temperatures from -80°C to -70°C, to reduce energy consumption and running costs as well as prolong the lifetime of ULT freezers. A self-reported list (94) with a variety of samples stored in ULT freezers with setpoint -70°C or higher has been made available by researchers from the United States to convince and engage others to ‘Chill Up’ their freezers.

The recommendations for actions found in the university sustainability programs refer to data collected in studies that are used to validate these recommendations. Therefore, a number of field test reports, with ULT freezer metering data, and publications (57,61,68,69,95–98) have been identified during the evaluation of the university-based sustainability programs, referring to the significant saving opportunities in energy consumption, costs and subsequently in reducing environmental footprint. This data provides a sound scientific basis for considering the use of energy-efficient ULT freezers, raising setpoint temperatures from -80°C to -70°C (energy savings between 20% and 40% are reported), and considering a wide range of other factors that can influence the efficiency of ULT freezers. A list of this sources can be found in **Appendix B.**

While there has been a lack of long-term studies on the sample integrity and simultaneously recorded energy consumption of ULT freezers at different temperatures, a novel study on this topic is being conducted by the University of Edinburgh, Roslin Institute (99). The study examines the impact of different storage temperatures (-80°C, -70°C and -60°C) on sample integrity of various samples types and simultaneously recorded energy consumption of ULT freezers in a 5 to 10 years period. The results of this study may further help in the discussion about what an appropriate storage temperature for various sample types might be. The results are not yet available.

Besides the energy-efficiency of ULT freezers, the impact of high heat loads from ULT freezers on HVAC (heating, ventilation and air conditioning) systems are discussed and selecting the best possible location for ULT freezers is also promoted by university-based sustainability programs.

In addition to the approach of reducing the energy consumption of ULT freezers in use, several actions promoted have in common to reduce the number of ULT freezers needed. Those include room temperature sample storage (RTSS), removal of unused and unnecessary samples (referred to as sample clear-out), consolidation of samples on box, rack and freezer level, maximizing sample vial efficiency and storing samples in a high-density format, sharing freezer space with others and having a clear, organized and up-to-date sample record system in place.

In order to reveal bad performing ULT freezers and reduce the risk of ULT freezer failures, breakdowns and subsequently the risk of sample loss, some university-based sustainability programs promoted to have a temperature and energy monitoring system as well as an alarm system installed with the ULT freezers. Moreover, in contrast, only a few university-based sustainability programs promote having in place emergency instruction in case of ULT freezer failure or breakdown.

Given the many opportunities to efficiently manage sample storage at ultra-low temperatures, several university-based sustainability programs promote to nominate a so-called ‘freezer manager’ being in charge of managing ULT freezers.

Within the topic of procurement considerations, in addition to the already mentioned ‘Energy Star’ label for ULT freezers, the ‘ACT’ eco-label from My Green Lab (100) is available for an informed purchasing decision as a measure for selecting more environmentally friendly options for laboratory products. There is a growing database of products bearing the ACT label (101), including sample storage tubes.

The results of this study have shown that the number of actions towards more sustainable storage of samples at ultra-low temperatures found in the university-based sustainability programs evaluated varies between 5 and 24 actions per university-based sustainability program, the extent of the individual programs therefore vary. However, what most of these programs have in common is an assessment framework combined with financial grants and award systems at different levels when participating in the programs or specific challenges. It is also worth noting that the universities whose sustainability programs have been evaluated all have an environmental policy, some of them have an externally accredited Environmental Management System (EMS), such as ISO 14001 (102), or are working on its implementation.

At this point it is important to mention the main organizations dedicated to laboratory sustainability, the non-profit organization My Green Lab (33) and the International Institute for Sustainable Laboratories (I^2SL) (103), both located in the United States, as well as the non-profit organization S-Lab (104) located in the United Kingdom.

My Green Lab seems to have the most comprehensive roadmap for the implementation of sustainable laboratory practices, including those for ultra-low temperature cold storage. Since 2017, My Green Lab and I^2SL have jointly initiated the international ‘Freezer Challenge’, where labs around the world are challenged by implementing sustainable cold storage practices (34). Over 8.5 million kWh have been already saved by the joint efforts of labs participating in the challenge (105) .

In addition to the scientific and educational community and non-profit organizations, the industry also plays an important and responsible role, for example by developing innovative sustainable products and integrating sustainability into their operations, which is being communicated through, e.g., Corporate Social Responsibility (CSR) Reports (106).

Several limitations have been faced during the evaluation of the university-based sustainability programs: The websites and their content of the university-based sustainability programs are all organized in a different manner, containing a lot of information in different formats (Best Practice Guides, Posters, Green-Lab Assessment Forms, Reports, Blog-Posts, etc.) and part of the information (like Green-Lab Assessment Forms) is restricted to a log-in area only accessible by university staff. The results are based only on publicly available resources from the Universities websites and therefore, it is likely that some potentially valuable information has been missed. Further, the analyzed university-based sustainability programs also include recommendations and measures concerning energy savings related to other equipment like e.g. fume hoods, water-savings, green chemistry and heating, ventilation and air conditioning (HVAC), subjects that may be applicable for biobanks in the sense of sustainable practices. Only those findings closely related to sample storage at ultra-low temperatures and ULT Freezers have been included in the analysis.

4.2 Discussion of the comparison of actions found in university-based sustainability programs to ISBER Best Practices

Within the scope of this study, it was further analyzed whether the 31 actions towards more sustainable storage of samples at ultra-low temperatures found in the university-based sustainability programs are mentioned in the ISBER Best Practices - 4th Edition, 2018 (52). Most notably, to my knowledge, this is the first study comparing sustainability measures practised and promoted in academic research to biobanking Best Practices.

These latest ISBER Best Practices provide a comprehensive guide for biobanks covering a wide range of technical, administrative, ethical and legal aspects, including planning considerations, technical considerations related to biobank facilities and equipment, quality management, safety, handling, processing and utilization of samples. These Best Practices have been developed with the overall aim of contributing to successful strategies to provide fit-for-purpose samples for research and harmonisation of biobanking activities (52).

In general, one of the key recommendations of the ISBER Best Practices (52) is to have a Quality Management System (QMS), containing Quality Assurance (QA) and Quality

Control (QC) programs, covering all operations of a biobank in place. Having a QMS in place contributes to the long-term sustainability of a biobank while supporting the goal of supplying high-quality samples and associated data for research (52).

The results of the comparison show that 16 (52%) of the actions found in university-based sustainability programs match with the ISBER Best Practices being substantially similar, identical or even going beyond the action promoted by university-based sustainability programs. Another 5 (16%) actions found in university-based sustainability programs are mentioned in a context variation and 10 (32%) actions are not mentioned.

Related to the comparison of actions in Category A "Green" Sample Management

All actions with their subject areas related to sample management are mentioned in ISBER Best Practices, whereas sample clear-out, having an inventory system in place, the choice of sample storage temperature, including the consideration of Room Temperature Sample Storage (RTSS) and sample labeling, match. Those are also the most frequently found actions towards more sustainable storage of samples at ultra-low temperatures related to sample management in university-based sustainability programs. The other actions related to sample vials, storage boxes and racks, and sample consolidation are mentioned in respect to their subject but with variation in the context. Whereas considerations related to sample vials, storage boxes and racks are not mentioned as an efficiency measure, sample consolidation is referring to automated storage systems capable of 'defragmentation', as an opportunity to maximize storage capacity (52).

Related to the comparison of actions in Category B "Green" Freezer Management

Looking at the actions related to the management of freezers, almost half of the actions found in university-based sustainability programs are mentioned and match to ISBER Best Practices. Those include the nomination of a freezer manager, selection of the best possible location for ULT freezers, keeping ULT freezer doors closed, ensuring proper airflow around the ULT freezer, temperature monitoring, having an alarm system installed with ULT freezers as well as having emergency instructions in place. Whereas almost the other half of actions related to the management of freezers found in university-based sustainability programs, is not mentioned in ISBER Best Practices. Those include the 'Chill-Up' of ULT freezers, by increasing the setpoint temperature from -80°C to -70°C, which is by far the most frequently found action related to the management of freezers found in university based sustainability programs. Although the ISBER Best Practices (52) recommend making every effort to reduce the costs for the operation of equipment in biobanks, ULT freezer 'Chill-Up' as an opportunity to do so is not mentioned. In general, it is recommended to carefully consider the impact of temperature on sample integrity as well as intended future analysis and duration of storage when choosing sample storage temperature (52).

Another frequently found action related to the management of freezers not explicitly mentioned in ISBER Best Practices, is sharing space by offering free ULT freezer space to others in order to reduce the number of ULT freezers needed in a department or institution, reduce overall energy consumption, resolve space problems, avoid buying additional ULT freezers and use ULT freezer space more efficiently. Comparing this action to ISBER Best Practices, a certain conflict arises when assigning the level of correspondence to 'not mentioned'. Although the ISBER Best Practices (52) mention that biobanks can generally be set up for an individual organization as well as for other organizations, sharing freezer space with others is not mentioned. By contrast, it is recommended to allow only dedicated biobank personnel to access the stored samples and to set up a security system and documentation (52).

At this point it must be noted that biobanks with their main activities, which among others are dedicated to the professionalised storage of samples, by offering their services to others can be fundamentally considered as a shared storage space. Thus, biobanks in general have the potential to use ULT freezers space more efficiently compared to single, individually operated freezers in academic research labs, especially when having a Quality Management System (QMS) in place.

Related to the comparison of actions in Category C Freezer Maintenance

The ISBER Best Practices (52), likewise the university-based sustainability programs, recommend to determine and perform routine assessment and adjustment of storage equipment according to the manufacturer's recommendations. However, not all actions related to freezer maintenance found in university-based sustainability programs are explicitly mentioned in the ISBER Best Practices.

Related to the comparison of actions in Category D "Green" Procurement Considerations

Further the ISBER Best Practices (52), likewise the university-based sustainability programs, recommend to find the most energy-efficient devices that meet the requirements before each purchase. Whereas university-based sustainability programs are relating this consideration solely to individual stand-alone ULT freezers, ISBER Best Practices (52) additionally mention that most cascade freezer systems, walk-in freezers and automated storage systems usually require a smaller footprint, lower HVAC (heating, ventilation and air conditioning) output and lower energy consumption compared to individual stand-alone ULT freezers. Whereas the initial costs for such storage systems are typically higher compared to individual stand-alone ULT freezer units, their lower energy consumption, increased storage capability and smaller footprint may pay off. Further considerations which may argue in favour of an automated storage system may include minimized temperature fluctuations, sample tracking and sample consolidation (49,52). Considering Eco-Labels as a measure of sustainability when making a purchasing decision is not mentioned in the ISBER Best Practices.

The differences between the actions found in university sustainability programs and ISBER Best Practices can be partly explained by the different objectives pursued by the respective organisations. Whereas the main objectives of the International Society for Biological and Environmental Repositories (ISBER) (83) are to contribute and share effective strategies to provide 'fit-for-purpose' samples for research and harmonisation of biobanking activities including scientific, technical, legal and ethical as well as managerial aspects, the common goals of university-based sustainability programs with their respective frameworks for laboratory sustainability aim to offer and implement strategies that can reduce the environmental footprint of laboratories, educate in respect to sustainable laboratory practices as well as empower and motivate the scientific community to be a driving force in sustainability.

4.3 Conclusion

The overall goal of this thesis was to emphasize the topic 'Environmental Sustainability' and to help to grow a culture of sustainability in the field of biobanking. This study is showing on the example of ultra-low temperature sample storage, that there is scope for improvement by implementing a number of sustainable practices to become more efficient, and to ultimately contribute to the Sustainable Development Goals. However, the results have been obtained from resources focusing on laboratory sustainability in university-based academic research. As a next step, it would be interesting to conduct a survey in order to find out to what extend the 31 actions towards more sustainable storage of samples at ultra-low temperatures found within the topics of sample management, freezer management, freezer maintenance and procurement considerations can and currently are being implemented in biobanks and how ultra-low temperature sample storage automation in contrast to manual ultra-low temperature sample storage can contribute to environmental sustainability in biobanking. In addition, it would be interesting to see how effective strategies for improving sample utilisation in biobanks can reduce the need for cold storage capacities and thus contribute to environmental sustainability in biobanking.

Although the activities of biobanks are crucial for the advancement in biomedical research and ultimately contribute to better health care and therefore play an important and responsible role for our society, the implementation of environmental sustainability in their operations would further contribute to the goals of sustainable development. Stakeholders, such as donors or funding sources will appreciate to see not only how samples, data as well as financial means are used for research, but also how biobanks care about environmental impacts and do their best to reduce them.

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Annex – A

List of evaluated university-based sustainability programs including weblink and date of access and evaluation.

Nr.	University	Country	Name of university-based sustainability program	Website URL	Date of access/evaluation
1	University of Bristol	UK	Sustainable Science and Green Labs	http://www.bristol.ac.uk/green/get-involved/green-labs/resources/	18.11.2019
2	University of Cambridge	UK	Green Labs	https://www.environment.admin.cam.ac.uk/green-labs	19.11.2019
3	University College London	UK	LEAF – The Laboratory Efficiency Assessment Framework	https://www.ucl.ac.uk/greenucl/resources/labs/leaf-laboratory-efficiency-assessment-framework	21.11.2019
4	The University of Edinburgh	UK	Social Responsibility and Sustainability	https://www.ed.ac.uk/sustainability	22.11.2019
5	Kings College London	UK	Sustainable Labs	https://www.kcl.ac.uk/aboutkings/strategy/sustainability/get-involved/staff/sustainability-champions/lab-champions/sustainable-labs	23.11.2019
6	University of California, Davis	USA	Green Lab Program	https://sustainability.ucdavis.edu/action/green_workplace/green_labs.html	26.11.2019
7	University of California San Francisco	USA	UCSF Green Labs	https://sustainability.ucsf.edu/getinvolved/greenlabs	29.11.2019
8	University of Colorado Boulder	USA	CU Green Labs Program	https://www.colorado.edu/ecenter/greenlabs	29.11.2019
9	Cornell University	USA	Green Lab Program	https://sustainablecampus.cornell.edu/programs-guides/green-office-lab-program/green-lab-program	29.11.2019
10	University of Michigan	USA	Sustainable Labs	http://sustainability.umich.edu/ocs/labs	29.11.2019
11	University of Pennsylvania	USA	Green Labs @ Penn Guide	https://www.sustainability.upenn.edu/penn-community/green-labs	29.11.2019

12	Stanford University	USA	Cardinal Green Labs	https://sustainable.stanford.edu/cardinal-green/cardinal-green-labs	30.11.2019
13	University of Washington	USA	Green Laboratory Program	https://green.uw.edu/green-laboratory	30.11.2019
14	Harvard University	USA	Green Labs	https://green.harvard.edu/programs/green-labs	30.11.2019
15	The Pennsylvania State University	USA	Green Labs	http://sustainability.psu.edu/green-labs	30.11.2019
16	Emory University	USA	Green Labs at Emory	https://sustainability.emory.edu/programs/green-labs-at-emory/	01.12.2019
17	University of Virginia	USA	Green Labs	https://sustainability.virginia.edu/programs/green-labs	01.12.2019
18	University of California, Santa Cruz	USA	UCSC Green Labs	https://sustainability.ucsc.edu/engage/green-certified/green-labs/index.html	05.12.2019
19	National Institute of Health	USA	NIH Green Labs Program	https://nems.nih.gov/green-teams/Pages/NIH-Green-Labs-Program.aspx	05.12.2019
20	McGill University	USA	Sustainable Labs Guide	https://mcgill.ca/sustainability/resources	06.12.2019
21	Princeton University	USA	Green Labs	https://ehs.princeton.edu/laboratory-research/laboratory-safety/green-labs	07.12.2019
22	The University of Queensland	AUS	Green Labs Program	https://sustainability.uq.edu.au/get-involved/green-labs-program	08.12.2019
23	The University of British Columbia	CAN	Green Labs	http://greenlabs.ubc.ca/	08.12.2019
24	Massachusetts Institute of Technology	USA	MIT Green Labs	https://greenlab.mit.edu/resources	08.01.2020

Annex – B

List of documents with ULT freezer metering data identified during the evaluation of the university-based sustainability programs.

Title	Website URL	Year from
Plug load test for ULT Freezers: 20-22% lower energy consumption at -70°C compared to -80°C	https://documentcloud.adobe.com/link/track?uri=urn%3Aaaid%3Ascds%3AUS%3A3d089b2b-451a-43d3-a3f1-73ecc216bcb5	2017
Ultra-Low Temperature Freezer Performance and Energy Use Tests	https://www.colorado.edu/ecenter/sites/default/files/attached-files/ucr_ult_tests_report_-_2016_final_df1.pdf	2016
Ultra-Low Temperature Freezers: Opening the Door to Energy Savings in Laboratories	https://www.etcc-ca.com/reports/ultra-low-temperature-freezers-opening-door-energy-savings-laboratories	2016
Efficient ULT Freezer Storage - An Investigation of ULT Freezer Energy and Temperature Dynamics	https://www.ed.ac.uk/files/atoms/files/efficient-ult-freezer-storage.pdf	2015
Field Demonstration of High-Efficiency Ultra-Low-Temperature Laboratory Freezers	https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/ult_demo_report.pdf	2014
Factors affecting the performance, energy consumption, and carbon footprint for ultra low temperature freezers: case study at the National Institutes of Health	https://www.inderscienceonline.com/doi/pdf/10.1504/WRSTSD.2013.050786	2013
Store-Smart Everything You Wanted to Know about Running an Ultra Low Temperature (ULT) Freezer Efficiently but Were Afraid to Ask…	https://hightech.lbl.gov/sites/default/files/documents/ULFFreezerUserGuide2013.pdf	2013
Environmental Profiles of Stirling-Cooled and Cascade-Cooled Ultra-Low Temperature Freezers	https://www.mdpi.com/2071-1050/4/11/2838	2012