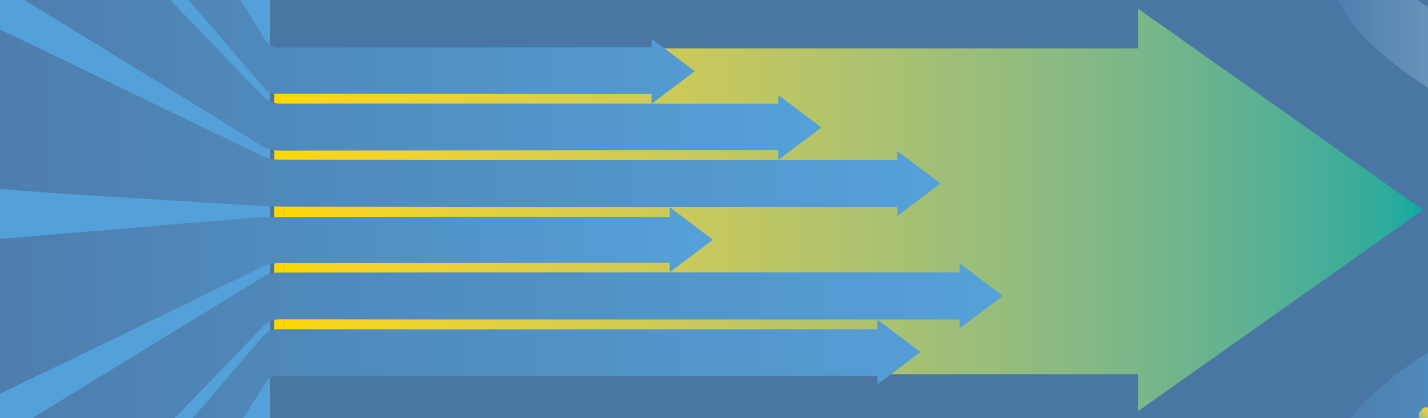
World Health Organization

Accelerating access to genomics for global health



Promotion, implementation, collaboration, and ethical, legal, and social issues

A report of the WHO Science Council

World Health Organization

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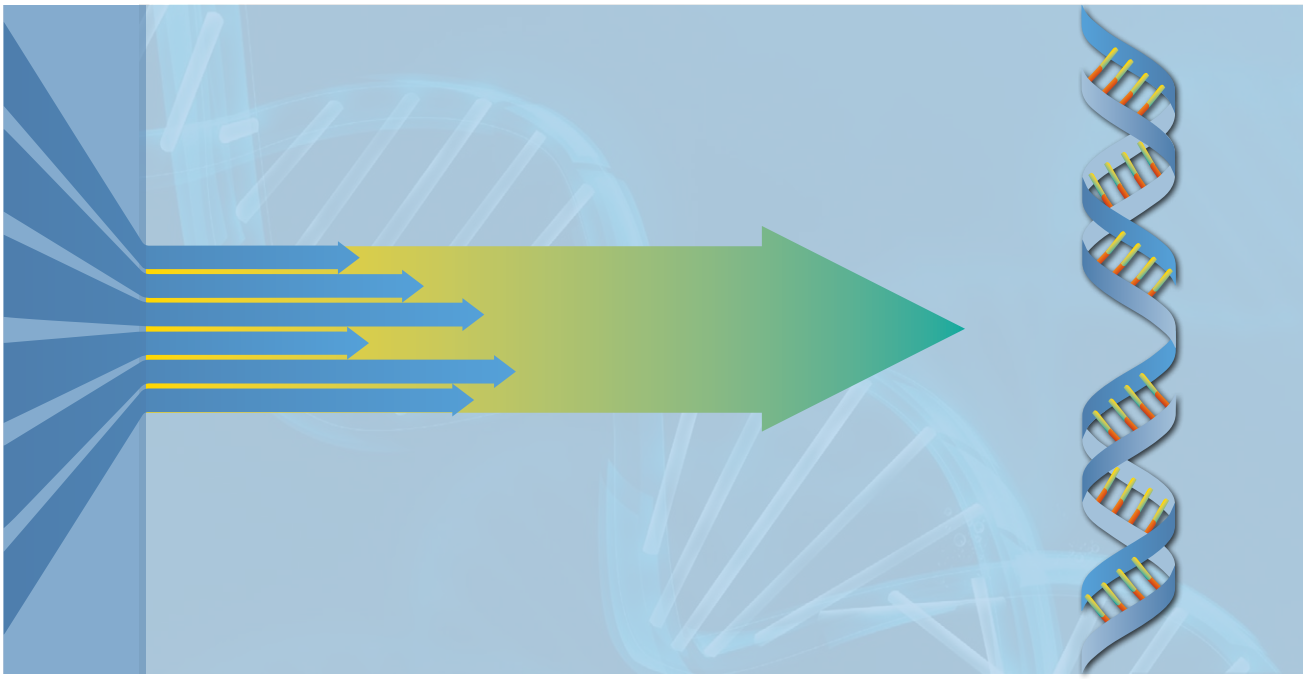
EXECUTIVE SUMMARY



Introduction and background

In 2021 WHO Director-General (DG) Dr Tedros Adhanom Ghebreyesus established the Science Council to advise him on WHO's scientific agenda.

At its first meeting, the Science Council identified genomics as the focus of this report, for a number of compelling reasons, chief among them, the substantial and extensive benefits of genomics for personal and public health. The ongoing COVID-19 pandemic has clearly demonstrated the importance of genomics for global public health. In addition, there are many examples of the successful uses of genomics in humans, animals, and agriculture in high-, low- and middle-income countries, as revealed during three international workshops convened by the Science Council.

The Council recognizes that there are many impediments to the implementation of expensive genomic technologies, especially in low- and middle-income countries, including high costs of equipment and reagents and lack of trained personnel. We are, however, convinced that current uses and future applications of genomic technologies are critical for improving the health and livelihood of people in all parts of the world, regardless of economic status, and that strategies to overcome the impediments are available.

Our report to the Director-General makes 15 recommendations for WHO and for consideration by multiple sectors within its Member States. The recommendations are grouped under four themes:

1. promotion of genomics through advocacy
2. implementation of genomic methodologies
3. collaboration among entities engaged in genomics, and
4. attention to the ethical, legal, and social issues (ELSIs) raised by genomics.

All four sets of recommendations are intended to accelerate the establishment of genomic technologies and to sustain their beneficial use. The Council has also concluded that a long lag time between the availability of genomic technologies in rich countries and their availability in less-resourced countries is neither ethically nor scientifically justifiable. We strongly support the early diffusion of genomic technologies throughout the world so that humankind can collectively derive the health and other benefits from genomics.

> **"Current uses and future applications of genomic technologies are critical for improving the health and livelihood of people in all parts of the world, regardless of economic status"**

Goals and recommendations

1 Promote the adoption or expanded use of genomics in all Member States through advocacy by many parties.

1.1 WHO should use its leadership role in global public health to advocate for the expanded use of genomics in its Member States. In particular, WHO should promote affordable access to genomic technology globally so that all Member States, especially low- and middle-income countries (LMICs), can adopt and expand the use of genomics for better health and other benefits. This will require persuading Member States, as well as commercial and non-commercial organizations, academic institutions, and others, of the medical, scientific, and economic benefits of genomic technologies.

1.2 Member States, especially LMICs, should develop and conduct advocacy programmes that support the adoption or expansion of genomics.

1.3 International, regional, and national professional societies in medicine, public health, and biomedical research should advocate for the uses and benefits of genomics.

1.4 WHO should establish a Genomics Committee to assess and report annually to the WHO Director-General on progress in implementing the recommendations in this report. This evaluation should encompass all four themes—promotion, implementation, collaboration, and ELSIs. The Genomics Committee should also be mandated to take up additional tasks (elaborated below in 2.1, 2.3, 2.4, and 4.1).

2 Identify and overcome the practical issues that impede the implementation of genomics through local planning, financing, training of essential personnel, and the provision of instruments, materials, and computational infrastructure.

2.1 WHO should provide guidance to Member States on best practices for implementation of national or regional genomic programmes.

2.2 Member States should establish national programmes for building or expanding genomic capabilities or join a regional programme.

2.3 Organizations in the genomics commercial sector should be convened by the Genomics Committee to develop and execute approaches to make their products and technologies affordable in LMICs.

2.4 Organizations in both the public and private sectors should develop and execute plans to enhance the training of individuals capable of making effective use of genomic technologies.

3 Foster commitments to collaborative activities to promote all aspects of national and regional programmes that advance genomics in Member States.

3.1 WHO should promote international collaborations on genomics by strengthening effective existing collaborative arrangements and by helping form new ones for specific needs.

3.2 Funding agencies should promote collaborative arrangements and encourage the participation of investigators, health care personnel, and computational experts from a diversity of disciplines to promote the optimal use of new genomic information.

3.3 Industry, academia, and civil society should collaborate on the use of genomics to help solve important health problems, especially those prevalent in LMICs.

4 Promote ethical, legal, and equitable use and responsible sharing of information obtained with genomic methods through effective oversight and national and international rules and standards in the practice of genomics.

4.1 WHO, working through its Genomics Committee, should be the custodian of guidance on how to deal with the ethical and social ramifications of genomics, including the global governance of genomic information.

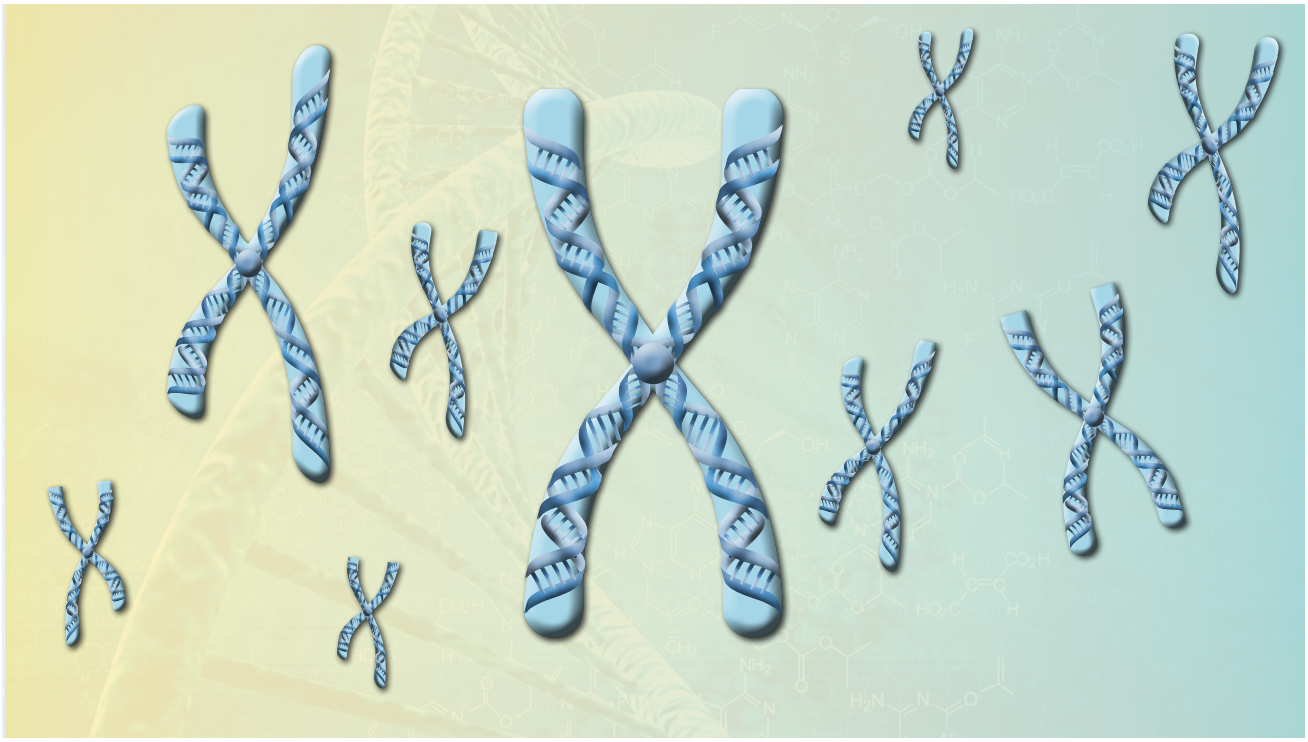
4.2 WHO should take a leading role in the resolution of debates about policies that govern the attribution of credit for genomics research.

4.3 Organizations in Member States, especially funding agencies, academic institutions, and governmental units should be attentive to ELSIs and to efforts being made by WHO and other international bodies to develop solutions to outstanding issues related to genomic ELSIs.

4.4 WHO should aspire to become the global authority on ELSIs for health-related genomic applications.

> **"WHO should use its leadership role in global public health to advocate for the expanded use of genomics in its Member States"**

INTRODUCTION



This is the first report of the WHO Science Council to Dr Tedros Adhanom Ghebreyesus, Director-General of WHO.

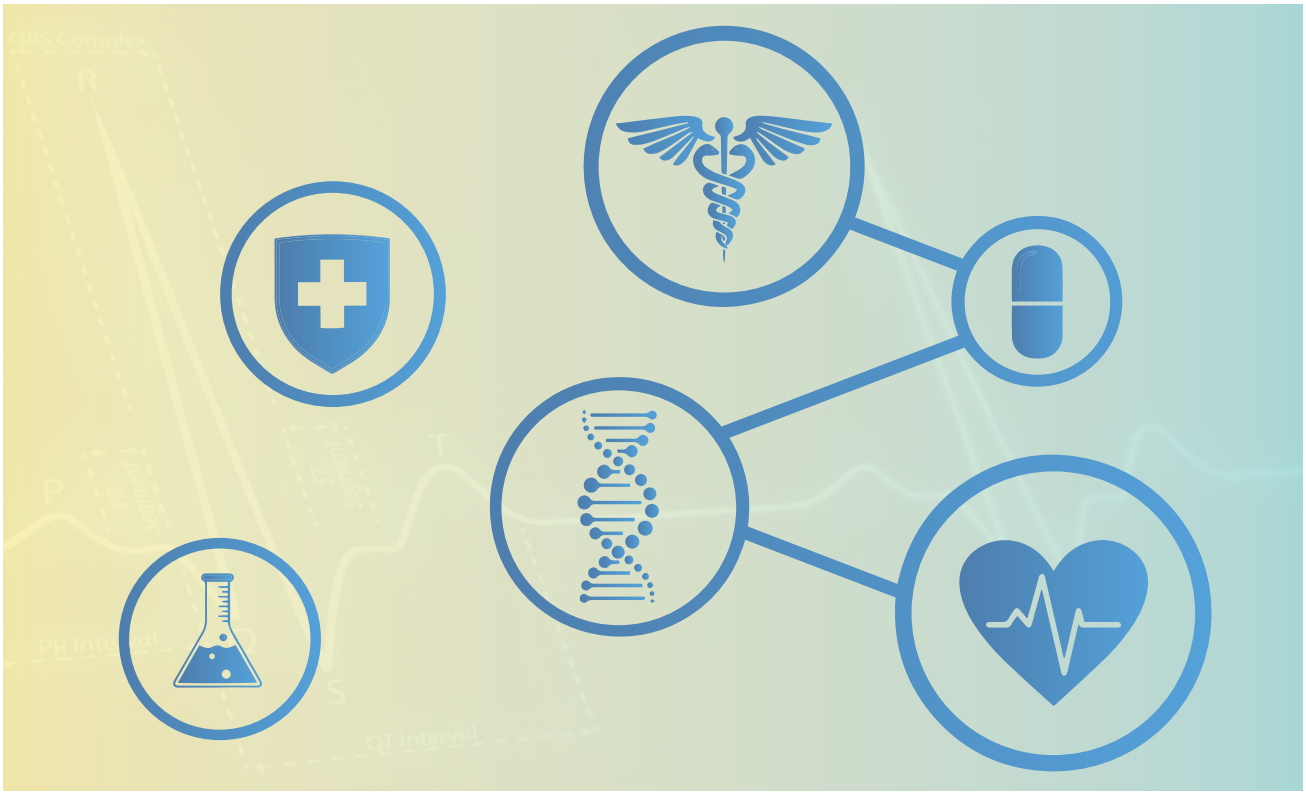
The DG established the Science Council in 2021 to advise him on WHO's scientific agenda. The specific requests were:

- To evaluate urgent, high-priority scientific issues and provide input and guidance on translating them into public health guidelines
- To identify emerging issues in science and technology that WHO needs to address, including global health threats and advances with the potential for direct or indirect effects on global health
- To provide strategic direction on WHO's work in science, research, and innovation
- To participate as needed in the rapid review of WHO's normative products.

At its inaugural meeting, held virtually on 27 April 2021, the Science Council identified genomics as the focus of its first report, given the significant implications for public health in many situations and in many places, especially the ongoing COVID-19 pandemic; the successful uses of genomics in humans, animals, and agriculture in high-, low- and middle-income countries; and the impediments to the implementation of expensive technologies, especially in low- and middle-income countries.

This report presents the Science Council's view of the current uses and future applications of genomic technologies, principally for improving the health of people in all parts of the world. The report features four sets of recommendations, directed to WHO and its Member States, which are intended to accelerate the establishment and sustained use of genomic technologies.

PART 1. BACKGROUND ON GENOMICS AND ITS APPLICATIONS IN THE HEALTH SCIENCES



1.1 What is genomics?

The relatively new and expanding field of genomics uses methods arising from biochemistry, genetics, and molecular biology to describe and understand biological information in chemical terms. Because health and disease are determined to a significant extent by such information, encoded in DNA and expressed in RNA and protein, genomic technologies have the potential to improve human health in profound ways. Many examples of such benefits of genomics have already emerged, especially in high-income countries (HICs).

The technologies used in genomic science are numerous and continue to expand. Those most fundamental to this field are designed to depict the biological information that is stored in genomes—the totality of genetic information in all animals, plants, and microbes, including viruses—as nucleotide sequences of DNA (or occasionally RNA). Sequencing, computational methods, and analyses are among the tools needed to perform these studies.

Genomics presents unique opportunities to address such public health issues as the global burden of disease and food security. Genomics

advances public health through the surveillance of pathogens, the provision of tools for medical care (in the prevention, diagnosis, management, treatment, and monitoring of disorders and diseases), and the improvement of food production. Genomics also enables basic and biomedical research that leads to new innovations.

1.2 A brief history of genomics

From 1975 through the early 1990s, scientists established protocols for DNA cloning (allowing the isolation of genes for study and sequencing of DNA); amplification (allowing portions of the genome to be copied, enabling further studies); sequencing; mapping; and bioinformatics, all of which laid the foundation for genomics.

Many papers have reviewed these advances, providing contextual insight into the steps in the development of new technologies, as well as perspectives on how the Human Genome Project was influenced by and encouraged the development of new technologies (1–5).

In the 20 years since the release of the first complete sequence of a human genome, the use of genomics has steadily increased in medicine, public health, and other fields. This uptake is attributed largely to the development of next-generation sequencing technology in 2005, which allows the generation of many millions of short reads of DNA sequence in parallel that can be detected without electrophoresis, coupled with faster throughput, and decreased cost, making sequencing accessible for many laboratories. Subsequent, ongoing improvements and competition continue to drive down costs (6).

With each sequence generated, there is an increasing accumulation of data and knowledge that, while incomplete and lacking in diversity representative of all populations, is a critical mass of information on which to build new knowledge of the human genome. The pioneering of genomics and hard-won successes in areas such as undiagnosed genetic diseases and cancer have advanced the integration of genomics in the medical setting.

The COVID-19 pandemic has focused intense global attention on the use of genomics to diagnose infection and to identify mutations in SARS-CoV-2 that lead to new variants with significant public health implications (Box 1).

1.3 Applications of genomics

Genomic applications are categorized in this report by their use in medicine, agriculture and aquaculture, biological and biomedical research, and others, as shown in Table 1. This table is an overview and not a comprehensive accounting of all current and potential applications.

> **"Genomics presents unique opportunities to address such public health issues as the global burden of disease and food security"**

In discussing the applications of genomics to human health, it is useful to distinguish between microbial and human genomics, since the analysis of microbial genomes does not present some of the ethical and legal issues—for instance, privacy and discrimination—that are inherent in descriptions of individual human genomes. The analysis of microbial genomes has become an essential feature of efforts to control infectious disease, with the goals of:

- Identifying and diagnosing infectious diseases
- Tracing the spread of infection through human and/or animal hosts;
  - Mapping the evolution of infectious agents
  - Assigning phenotypic properties, such as infectivity and pathogenicity, to specific genes

- Evaluating an infectious agent's sensitivity or resistance to drugs.

Human genomics is used to prevent, diagnose, predict, manage, monitor, and treat genetic conditions. These aims are met by:

- Evaluating carrier status for a genetic disorder
- Diagnosing of select chromosomal conditions, such as trisomy 21
- Screening for and diagnosis of single gene disorders
- Assessing disease susceptibility or predisposition to many chronic illnesses
- Determining whether a genetic mutation is present in germline (thus heritable to future offspring) or somatic (due to a new variant that has occurred at some point in the person's life)
- Establishing disease prognosis
- Monitoring of drug resistance during treatment and modifying therapy
- Selecting medications based on mechanism of action or genetic determinants of metabolism to reduce toxicities.

Agriculture and aquaculture genomics can be used to understand and select the genetic traits of plants, animals, and insects that will support and improve food production. These aims are met by:

- Cataloguing of genetic diversity in the wild and in founder stocks
- Assessing genetic profiles for health and commercial traits
- Predicting susceptibility and responses to environmental stress
- Selecting preferred crops, animals, and insects.

Genomics also can be used for:

- Ancestry, including the establishment of parentage
- Environmental studies to predict how an organism will respond to environmental change
- Forensics for identification purposes
- Many basic science and biomedical research applications.

Genomics can be applied in different ways.

Genomics can be used to examine all relevant genomes. For example, the study of malaria infections benefits from the examination of multiple genomes—those of the protozoa causing it, the mosquito transmitting it, and the human who is infected. Microbial genomics is used for studying pathogen prevalence, evolution, pathogenesis, diagnosis, disease course, and response to vaccines and therapies, and human genomics for studying susceptibility, immune responses, and co-morbidities.

> **"Human genomics is used to prevent, diagnose, predict, manage, monitor, and treat genetic conditions"**

Genomics can be applied at the individual and population levels. Genomic tests for an individual's genetic attributes or for the frequency at which a genetic trait appears in a population may be the same, but the rationales and uses differ. In the former situation, personal and family histories are the rationales for genomic testing to evaluate an individual's health risks, whereas in the latter case, public health concerns may justify genomic screening of either whole populations or subpopulations of asymptomatic individuals to assess risks for certain medical conditions. Another population level approach of relevance is surveillance of wastewater for pathogens and their variants.

Genomic testing can be performed for use in clinical or research applications. Test results that are used in the care of patients are required to meet clinical laboratory standards according to strict protocols, including the establishment of test quality and performance.
Genomics information can be combined with

other kinds of data. For example, there is a useful interplay among the "omics"—the encyclopaedic approach to gathering large amounts of information about metabolism (metabolomics), proteins (proteomics), genomes (genomics), and other features of living systems. The associations among data obtained with these and other new high-throughput technologies are important components of modern biomedical research. Interpretation of new genomic data is also usually dependent on pre-existing information about normal and variant genomes, from both human and other organisms and from pathogens, stored in accessible databases.

> **"The aims of genomic programmes should be based on national or regional needs and are influenced by population structure, disease prevalence, economic status, and competing priorities"**

Several relatively recent and expensive genomics technologies, such as gene editing, gene therapy, and complex methods (such as single cell genomics), are not included in this report. Our recommendations for implementation focus on the subset of genomics technologies (for example, polymerase chain reaction, DNA and RNA sequencing, bioinformatics) that are most commonly used, accessible, and not prohibitively expensive for broad use.

1.4 Economic, social, and environmental benefits

A full analysis of the economic costs and benefits of genomics is beyond the scope of this report but anticipated benefits include direct stimulus to the commercial for-profit sector that produces machines and reagents and provides services; job creation in academic, medical, and commercial positions; and tax revenue on sales and wages for governments, and indirect stimulus through improvements in population health (improved medical care, quality of life, potentially decreased health care utilization) and the creation of intellectual property rights. Canada, Thailand, and the United Kingdom of Great Britain and Northern Ireland have each made large investments in genomics, reflecting a perspective on genomics as an opportunity for economic advancement.

Rigorous academic studies on the economics of genomics, such as cost-minimization analysis, cost-benefit analysis, cost effectiveness, and cost utility have been lacking for genomics (7) but are starting to be performed. These include economic analyses on the benefit of whole genome sequencing for newborns (8) and hypothesized cost savings from increased diagnostic yield for undiagnosed genetic diseases (9).

In addition to economic benefits, genomics plays a crucial role in generating social and environmental benefits, enabling progress in several United Nations Sustainable Development Goals, especially Goals 1–3, concerning poverty, hunger, and health, respectively. Further, it helps in national and international efforts to conserve marine and land resources (Goals 14 and 15).

1.5 Requirements and considerations for implementation of genomic methods

The aims of genomic programmes should be based on national or regional needs and are influenced by population structure, disease prevalence, economic status, and competing priorities. Input from a variety of sources (such as Ministries of Health, Education, Science and Technology, health care providers, public health networks, etc.) and stakeholders will help identify these needs.

Stakeholders in genomics include the patients and families who undergo clinical genomic tests or participate in research; the workforce to support, perform, analyse, and convey the results of genomics; researchers who devise methods and

validate applications; professional organizations that bring expertise, conduct training, organize conferences, provide advocacy, and recommend community standards for genomics; the health care, insurance, educational and commercial sectors; and public health networks and government at local, country, and regional levels.

New genomic programmes also require lab space, equipment, reagents, and other supplies; access to information technology resources, including computing capacity, data handling, storage, security, and the workforce needed for sample collection, processing, analysis, and delivery of results and clinical actions based on the findings. The biggest initial cost is for equipment, such as sequencers, while the biggest ongoing cost is for reagents that remain under patent protection.

A recently published WHO guide to assist Member States in building genomics capacity during the COVID-19 pandemic (10) provides a useful framework for considering the stages of implementation: defining aims and stakeholders; considering technical and logistical components; ensuring a safe and ethical environment; data sharing; and programme evaluation.

Making genomics affordable for LMICs remains a significant obstacle to implementation, as the cost for sequencing remains high for health systems, researchers, and most patients paying out of pocket. However, some methods for reducing the costs of expensive treatments and technologies have emerged from recent work in global health, especially in efforts to control HIV/AIDS, and will be discussed in later sections of this report.

1.6 Ethical, legal, and social issues

Genomics methods span a multitude of applications of relevance to health. This has two dimensions: bringing opportunity to both understand and improve response to disease if implemented appropriately and, on the other hand, creating risks to society if genomics methods are implemented without due attention to ELSIs. When genomic information is derived from human subjects (either patients or research subjects), it has the potential to violate privacy, create the possibility of discrimination in employment and insurance, confer inappropriate financial gain, or convey cultural disrespect. In other situations, such as in the surveillance and investigation of pathogens, this information has very limited potential to pose threats to individuals. Insufficient protection of participants and the data they provide risks the abuse of genomic information, while unduly restrictive rules about the generation, sharing, and use of genomic information limit the benefits that such information can provide.

“New genomic programmes require lab space, supplies, access to information technology resources, and the workforce needed for sample collection, processing, analysis, and delivery of results and clinical actions based on the findings”

Box 1. Genomics during the COVID-19 pandemic

The COVID-19 pandemic illustrates the power and complexities of using genomics to combat infectious diseases.

Generation and sharing of viral genomic data. Next-generation sequencing was used to determine the sequence of the RNA genome of an initial isolate of the coronavirus named severe acute respiratory syndrome coronavirus type 2 (SARS-CoV-2). The release of sequencing information in January 2020 was immediately used for the development of nucleic acid-based tests, the design of RNA- and protein-based vaccines, and research on mechanism-based therapeutics—all critical steps in combatting COVID-19 (11). Subsequently, sequencing data became the basis of global monitoring of the evolution of the virus and the emergence of new viral variants.

The example of South Africa. Since South Africa has the highest burden of HIV and the largest AIDS treatment programme in the world, it has built up substantial capacity, with government support, to undertake viral gene sequencing, principally to monitor the development of antiretroviral drug resistance and viral transmission patterns. In March 2020, this capacity pivoted to monitoring mutations in the SARS-CoV-2 genome. Genomic surveillance was initiated in South Africa and then, in partnership with Africa CDC, played a key role in supporting SARS-CoV-2 phylogenetics in the whole of Africa. This support included helping build laboratory sequencing capabilities and bioinformatics analytic capabilities in several countries in Africa.

Drawing upon this well-established genomic surveillance capacity, South Africa has been at the forefront of identifying new viral variants. In November 2020, scientists in South Africa's national genomic sequencing consortium identified a group of patients in the eastern Cape with three unusual mutations in positions 417, 484, and 501 in the Receptor Binding Domain of the virus and shared this information at a WHO SARS-CoV-2 genomic monitoring committee meeting. Using this information, researchers in the United Kingdom reviewed their viral sequence data, only to discover that a variant with a mutation at position 501 was already in circulation in the United Kingdom. The United Kingdom announced the discovery of its variant (later named Alpha) on 14 December 2020, with South Africa announcing the finding of its variant (later named Beta) three days later. These variant discoveries changed the world's understanding of how the pandemic would evolve.

In late November 2021, researchers from South Africa announced the discovery of the Omicron variant, with more than 50 mutations. After this announcement, several countries, including Canada, the United Kingdom, and the United States of America imposed immediate travel bans on several African countries, without regard as to whether they had reported local transmission of the Omicron variant. Despite this, the highly infectious Omicron variant spread to almost every country in the world, indicating the failure of discriminatory travel bans to curb the spread of the virus. This new variant led to a sea change in the global understanding of how the virus was evolving. A few months later, South African scientists announced the discovery of two new Omicron sub-variants, BA.4 and BA.5, which drove a new wave of infections in the country. A highly developed genomic capacity has enabled a country like South Africa to make a major contribution to the understanding of and response to COVID-19 globally.

Development of sound public health practices. The sequence of SARS-CoV-2 in hand, public health organizations were able to use genomic methods, such as reverse-transcription polymerase chain

Box 1. Genomics during the COVID-19 pandemic (cont'd)

reaction (RT-PCR, a method that amplifies viral RNA sequence if it is present in a sample) and rapid antigen testing (a method based on interaction between the antigen in the test and the proteins on the virus if present) in surveillance efforts.

Countries with a public health infrastructure and network of laboratories in place for influenza, Ebola virus disease, antimicrobial resistance, and HIV in place were able to mobilize resources more quickly. Overall, public health system capacity for global sequencing has increased to 68%, a 14% increase since the pandemic began (12).

Global agreements, norms, and standards. WHO has been critical throughout the pandemic in facilitating agreements, establishing norms and standards, and in underscoring the importance of strengthening the global public health infrastructure.

Data sharing and attribution. The importance of attribution for the data generated by researchers in countries across the world received attention during the pandemic, along with a newfound appreciation for the time and effort needed to generate the data, especially among those who were also on the frontlines of the response.

Discrimination and stigma. The identification of variants of concern led to discrimination and stigma towards countries in which the variants were initially identified, in some cases, resulting in the closing of borders to trade and travel and the creation of damaging narratives that negatively portrayed countries despite the global benefits of the information they provided.

Box 2. Cancer genomics

As clinical practice moves towards greater precision, especially in HICs, genomic technologies are having profound effects on several aspects of cancer, including prevention, diagnosis, treatment, and research.

Diagnosis and classification of tumour types. The sequencing of DNA from tumours and comparison with DNA from normal tissue is now performed at many cancer centres and provided by several commercial laboratories. The major goal is to identify "somatic mutations", those changes that have occurred in the sequence or organization of DNA during a patient's lifetime to initiate cancerous growth and determine the behaviour of cancer cells. The tests can analyse small panels of selected genes, the entire repertoire of protein coding sequences (exomes), or entire genomes. They can also reveal the involvement of cancer-causing viruses, such as Epstein-Barr virus or human papillomaviruses, in the pathogenic process.

Combined with the traditional tools of pathology (characterization of tumour tissue under the microscope), these genomic methods can establish a highly precise and informative diagnosis, guide life-extending choices of treatment, and gauge probable outcomes. Large collections of such genomic data (e.g., The Cancer Genome Atlas at the National Cancer Institute in the United States of America [13] or the COSMIC database at the Sanger Centre in the United Kingdom [14]) increasingly inform the classification and investigation of different cancer types. Of note, however, the data come largely from patients of European descent and do not yet proportionally represent the diversity of human ancestries.

Selection of treatments. Information about somatic mutations is now often used in HICs to select treatments, especially the so-called "targeted drugs", which inhibit the mutant proteins that drive the behaviour of cancer cells. This is done most often for cancers of the blood, lung, gastro-intestinal tract, breast, and skin. Further, when cancers become resistant to such treatments, new drugs can often be prescribed, in accord with changes detected through additional genomic tests.

Inform prognosis and monitor for recurrence. Aspects of a cancer's genome can often be used to predict the severity and likely outcome of the disease. Moreover, tests for cancer cell DNA in a patient's blood can be used to determine whether treated patients are in remission or in early stages of recurrence.

Determine hereditary risks of cancer. The likelihood of developing several kinds of cancer can be influenced by the inheritance of variants in certain genes, such as *BRCA1* or *BRCA2*, *TP53*, or genes governing repair of damaged DNA. Genetic tests for such variants, especially in families with higher-than-average rates for certain cancers, can help reduce cancer mortality by frequent surveillance for early tumours or by removal of target organs.

Table 1. Applications and uses of genomics

This table is an overview and not a comprehensive accounting of all current and potential applications.

Application	Use
Human genomics for medical purposes	• Risk assessment (carrier screening, prenatal screening tests, newborn, child, and adult screening) • Diagnosis of disease, both single gene and common disorders • Treatment selection, including pharmacogenomics to target therapies and reduce adverse events, gene editing, and gene therapy • Disease prognosis and monitoring
Microbial genomics for medical purposes	• Identification of infectious agents and development of diagnostic tests for the disease • Contact tracing of infectious agents • Investigation of cluster outbreaks to identify potential sources of the infectious agent • Mapping chains of transmission of infectious agents within a community • Assessment of characteristics such as infectivity and severity of associated disease • Design of vaccines and prediction of responses to vaccines and medications
Agriculture and aquaculture genomics	• Catalogue of genetic diversity in the wild and in founder stocks • Identification of new traits and disease susceptibility • Selection of traits in genetic programmes
Biological and medical research	• Discovery of genes influencing disease • Rational drug development • Identification of genetic signatures in combination with other biomarkers
Other	• Assessment of ancestry and parentage • Environmental and ecological sciences • Forensic science

PART 2. RECOMMENDATIONS: ACTIONS FOR ADVANCING THE USE OF GENOMICS IN ALL MEMBER STATES

In this part of our report, we make a series of recommendations to WHO and to constituencies within its Member States—governments, academia, industry, health advocacy groups, professional societies, and others—for advancing genomics. We address these recommendations to countries at all levels of economic development so that the benefits of genomics—primarily for health, but also for economic security and other benefits—may be experienced globally.

We make these recommendations within a framework that emphasizes four broad and occasionally overlapping themes: promotion of genomics through advocacy; implementation of genomic methodologies; collaboration among entities engaged in genomics; and attention to the ethical, legal, and social issues raised by genomics.

Within each of the four domains, we provide a summary of the rationale for our recommendations. The recommendations are based on public reports, the experiences of our members and consultants, and three workshops that were held in 2021 to gather information (see Annex 1). Evidence presented at these three workshops illustrated the benefits of genomics in clinical care and public health as well as in agriculture; the declining costs of establishing and expanding genomic technologies; the enhanced recognition of the value of genomics during the COVID-19 pandemic; and progress towards resolving the related ethical, legal, and social issues.

THEME 1: PROMOTION

The case for advocacy for the expanded use of genomics is based on both demonstrated benefits and anticipated utility. This is most forcefully illustrated by the role played by microbial genomics during recent infectious disease outbreaks, especially the COVID-19 pandemic. But the case also includes other applications in human health (microbial surveillance and screening, prevention, diagnosis, and treatment of many diseases and disorders), in agriculture and aquaculture, and in research in the biological sciences, as described earlier. The case for advocacy also depends on the evidence for indirect benefits for economies, cultural studies, and forensics.

At its workshops, the Council heard evidence for the increasing feasibility of implementing the required technologies for many beneficial applications in all parts of the world, including LMICs (see Annex 3). These examples support the need to advocate for programmes and policies that will foster genomics on multiple levels—research and development, workforce training, construction of genomics facilities, and use. However, information about the benefits of genomics has not been widely appreciated, especially in LMICs, where genomics is feasible but currently underutilized—hence, the need for advocacy.

In the past, there was a long lag period between the time when new technologies were made available in wealthy countries and when they eventually cascaded down to poorer countries as costs declined. The lag period, which creates global inequity, is neither ethically nor morally justifiable, especially now that tools to reduce or eliminate that gap are now tested and available. These tools include tiered pricing, controlled sharing of intellectual property rights for low-cost versions, and cross-subsidization; these and others have been used successfully, for example, to make the latest technologies for HIV diagnostic tests and treatments readily available in all countries. In this report, we strongly support the early diffusion of genomic technologies with little or no lag across the globe so that humankind can collectively derive the health benefits from genomics.

Goal: **Promote the adoption or expanded use of genomics in all Member States through advocacy by many parties.**

Recommendations

Organizations and individuals with the knowledge, resources, and influence to serve as advocates should make the uses and benefits of genomics more widely known. They should also encourage others to join advocacy campaigns, as part of efforts to bring the benefits of genomics to everyone in an effective, ethical, and equitable manner. The messages should be clear and compelling on the many benefits of genomics, providing balanced presentations that include accounts of difficulties and examples of specific successes, as well as information based on and thus applicable to local needs and priorities, especially in LMICs. Because of significant costs and complexities, strong advocacy campaigns will be required to use genomics appropriately to improve the study, prevention, diagnosis, treatment, and monitoring of disease and to reap the benefits of genomics in fields other than medicine.

1.1 WHO should use its leadership role in global public health to advocate for the expanded use of genomics in its Member States. In particular, WHO should promote affordable access to genomic technology globally so that all Member States, especially LMICs, can adopt and expand the use of genomics for better health and other benefits. This will require persuading Member States, as well as commercial and non-commercial organizations, academic institutions, and others, of the medical, scientific, and economic benefits of genomic technologies.

WHO has the capacity to disseminate useful and reliable information (such as an advocacy tool kit) to political and financial decision makers in Member States for several purposes:

- to provide educational programmes (for example, through the WHO Academy) related to the benefits of genomics for health and other purposes
- to suggest ways to integrate genomics in the short- and long-term planning of other WHO programmes
- to monitor and evaluate the success of advocacy programmes to encourage adoption and maintenance of useful strategies
- to offer technical assistance for implementation of genomic technologies (financing, equipping, training, and other activities are described below under Theme 2).

WHO should make use of these capacities and submit an annual report of recent and planned WHO activities in genomics to be used by the Genomics Committee proposed below in Recommendation 1.4.

WHO should also use its convening power, perhaps through the new Genomics Committee, to assemble the manufacturers of technologies, equipment, reagents, etc, together with activists, scientists, and others to encourage companies to find ways to make their products more accessible in LMICs.

In advocating for genomics, WHO should consider all stakeholders, including the lay public, not just governments, businesses, and professional organizations. Public education and engagement can create an informed basis for trust, encouraging participation in research and public health initiatives. WHO should also use its convening power and global leadership role to promote collaborations (as described below under Theme 3).

1.2 Member States, especially LMICs, should develop and conduct advocacy programmes that support the adoption or expansion of genomics.

Political leaders and other influential citizens of Member States should encourage their Ministries of Finance, Education, Health, and Science and Technology to work together to coordinate advocacy and provide guidance and resources for the implementation of genomics for health and other applications.

1.3 International, regional, and national professional societies in medicine, public health, and biomedical research should advocate for the uses and benefits of genomics.

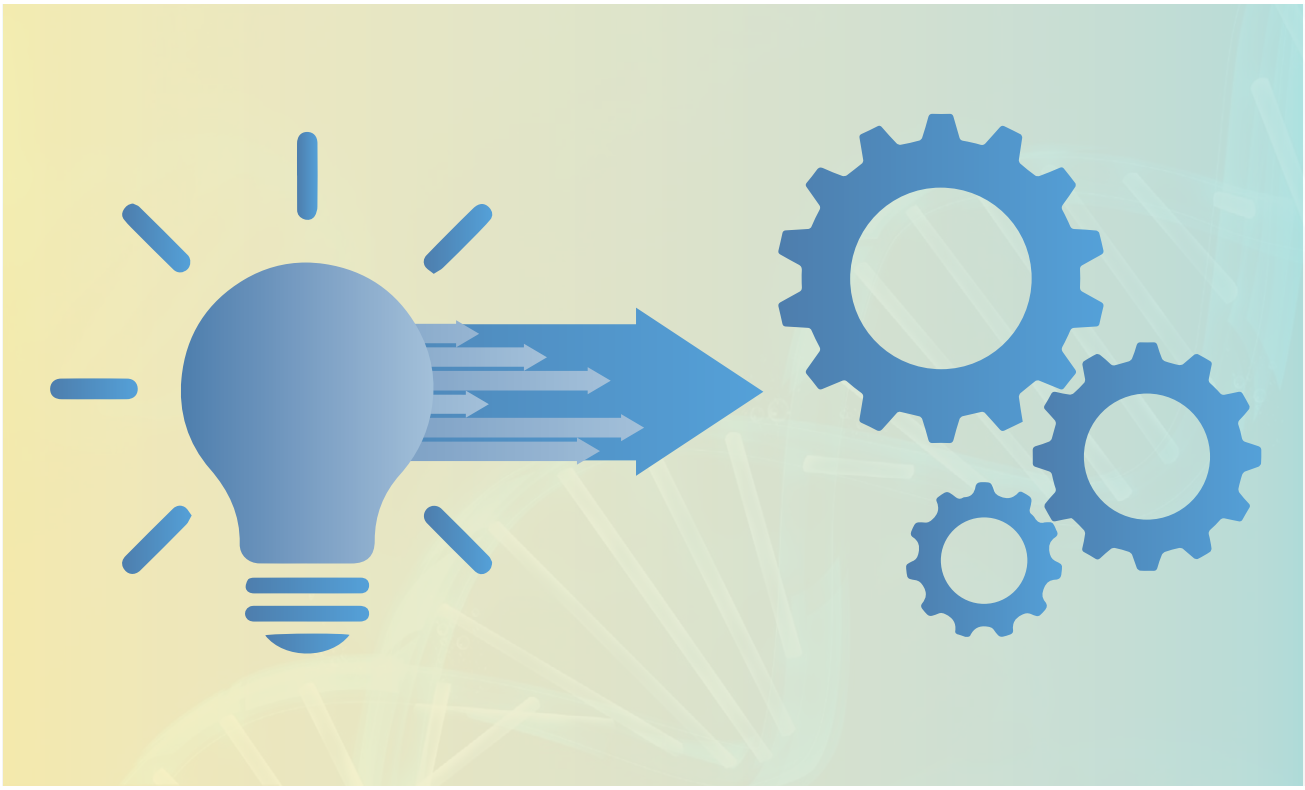
These professional societies should develop and make widely available information about genomics and its benefits, targeting their messages especially to political and governmental leaders, teachers of students at all levels, and commercial institutions with business interests related to any aspect of genomics.

1.4 WHO should establish a Genomics Committee to assess and report annually to the WHO Director-General on progress in implementing the recommendations in this report. This evaluation should encompass all four themes—promotion, implementation, collaboration, and ELSIs. The Genomics Committee should also be mandated to take up additional tasks (elaborated below in 2.1, 2.3, 2.4, and 4.1).

Within a year after issuance of this report, the DG should appoint several well-credentialed genomics experts as members of the new Genomics Committee. The DG should direct the panel to undertake a rigorous review of the steps taken by WHO, its Member States, and others to whom our recommendations have been directed and to propose additional steps to remedy any deficiencies in responses to this report. The intention is to improve the likelihood that the recommendations in the report are effectively implemented.

> **“WHO should promote affordable access to genomic technology globally so that all Member States, especially LMICs, can adopt and expand the use of genomics for better health and other benefits”**

THEME 2: IMPLEMENTATION



Genomic methods are lacking or nascent in many LMICs. As a result, Member States have varying capacities for performing and interpreting genomic procedures, such as DNA and RNA sequencing (12), and their citizens are less likely to be included in international genomic initiatives (15, 16). These national and regional inequities in access to genomic technologies are not surprising, since such technologies require several factors that are especially limited in LMICs: financing, infrastructure, materials, and highly trained personnel. Based on information reviewed for this report, the Science Council has concluded that it is possible for LMICs to overcome the obstacles posed by these limiting factors, especially with the assistance of long-term planning, support from other countries, and multi-sectoral collaboration. Without such measures, the benefits of genomics are unlikely to be experienced broadly and unequal access to new genomic technologies is likely to persist.

Successful implementation requires the engagement of many sectors of society and attention to a wide variety of needs. Governments and funding organizations, as well as the commercial and academic sectors, need to commit to the fundamental principle that investing in genomic technologies, even in LMICs, is a valuable enterprise. More specifically, it requires commitments of financial resources; equipment and reagents for laboratory work; computational tools for data management and storage; the construction and maintenance of facilities; and the training and support of a workforce that serves all phases of genomics, from laboratory work to data analysis and management, to the use of data in public health and clinical care.

Goal: **Identify and overcome the practical issues that impede the implementation of genomics through local planning, financing, training of essential personnel, and the provision of instruments, materials, and computational infrastructure.**

Recommendations

2.1 WHO should provide guidance to Member States on best practices for implementation of national or regional genomic programmes.

As part of its advocacy for genomics, WHO should provide expert advice about the development of strategic plans for the implementation and expansion of national or regional genomic programmes. Such planning should begin with national and regional inventories of existing genomics capacities. WHO and Member States should work with professional organizations that specialize in genomics (such as Global Alliance for Global Health (GA4GH) and others listed in Annex 1) to compile the requirements for implementation; assess the availability of each component for individual locations and anticipated uses; and develop strategies for obtaining what is needed to operationalize plans.

In addition, WHO should ask its Economics Council to evaluate the business case for investments in genomics in individual countries or regions, including special customs and tax considerations, to reduce the risk of financial burden caused by such investments.

Because of its close attention to legal and ethical issues, WHO can also provide perspectives on and promote an understanding of which applications of genomics and which elements of genomic information are likely to raise ethical concerns in certain contexts.

WHO can also promote understanding of the interconnection of the uses of genomics from clinical domains (e.g., diagnosis, disease management, genetic counselling, antimicrobial resistance prediction), to epidemiology (e.g., outbreak investigation using phylogeny, identification of zoonotic spillovers) and research (e.g., mechanistic investigations, genetic bases for antimicrobial treatment susceptibility, and drug and vaccine development) (12).

2.2 Member States should establish national programmes for building or expanding genomic capabilities or join a regional programme.

National and regional programmes should draft strategic plans that identify priority areas for implementation of genomic technologies, according to public health, medical, and other societal needs. These genomics programmes should have a governance structure that ensures collaboration among Ministries of Finance, Health, Education, and Science and Technology, with the inclusion of relevant organizations, health care providers, academia, the private sector, and sectors outside health, as appropriate.

Member States should ensure sustainable funding for capacity-building, infrastructure development, and the conduct of cost-effective programmes. National and regional plans should include elements that capitalize on bundling or scaling for procurement, supply, and maintenance of equipment and materials, and collaboration in training of essential personnel. Funding might come partially and initially from international collaboration, but for the long term, Member States will need to ensure the availability of their own resources. These plans and the progress made towards achieving their goals should be part of annual reports to the WHO Genomics Committee (see Recommendation 2.4).

2.3 Organizations in the genomics commercial sector should be convened by the Genomics

Committee to develop and execute approaches to make their products and technologies affordable in LMICs.

Those in the commercial sector who sell equipment (e.g., sequencing machines and computers), reagents for sequencing and other technologies, and software for data management) should play a crucial role in fostering the growth of genomics and capacity-building, including making genomic methods affordable, especially in LMICs, through cost reduction, low-interest loans, and gifts, dedicated and reliable advice, and other philanthropic activities.

> **"Organizations in both the public and private sectors should develop and execute plans to enhance the training of individuals capable of making effective use of genomic technologies"**

Commercial and industrial firms that sell equipment and reagents for genomics should consider the establishment of and contribute to an International Genomics Industrial Affiliates Fund to help support the growth of genomics, including training activities (see 2.4 below).

2.4 Organizations in both the public and private sectors should develop and execute plans to enhance the training of individuals capable of making effective use of genomic technologies.

The responsible implementation, use, maintenance, and application of genomic methods and results require a workforce well trained in a diversity of disciplines. The necessary skills include the ability to conduct genomics tests accurately and efficiently; to service the equipment and other facilities used in genomics; to identify human subjects for whom testing is appropriate; to interpret, manipulate, store, and analyse genomic data; and to deliver findings and recommend appropriate next steps to tested individuals. Acquisition of these skills can occur in a variety of ways and sometimes through established programmes in academia or industry that produce sophisticated technicians, genetic counsellors, physicians specializing in medical genetics, and others. But appropriate training programmes for essential local genomic functions are often not available. Thus, any national planning process for implementation of genomics must give serious attention to the ways in which people will be trained and nurtured to cover the full range of activities essential to the medical uses of genomics.

Local and national governments, educational institutions, funding agencies, foundations, and others should develop and deploy training programmes that can provide the skilled workers required to conduct genomic work. Training needs to be evidence-based and designed in accordance with the needs of individual countries and regions. It should include a wide range of interventions: training new scientists to use genomics; expanding the skills of current scientists; integrating genomics into undergraduate, medical, and nursing educational programmes; and incorporating genomics into clinical practice through programmes in genetic counselling. Efforts should also be made to increase the understanding of genomics among members of the public. Investment in a genomics-literate workforce will be critical to the sustainability of genomics in public health and will prepare health systems to reap the benefits of genomics.

The Science Council places special emphasis on the need for such training programmes to provide the personnel essential for success of genomics, especially in countries that have previously had limited or no access to genomic technologies. The Council therefore strongly recommends the inclusion within each country's strategic plan

of training programmes designed to meet the specific needs of that country. Such programmes should include efforts both to recruit students early in their educations and to provide training in genomics for citizens already educated in general biology or computational sciences. Funds to support educational programmes should be sought from commercial vendors, who have much to gain from greater use of the machines, reagents, and software that their companies produce.

Finally, in view of the centrality of a trained workforce to the practice of genomics, each Member State should include an assessment of its genomics workforce and options for additional training in an annual report to WHO through the Genomics Committee.

"The Science Council places special emphasis on the need for such training programmes to provide the personnel essential for success of genomics, especially in countries that have previously had limited or no access to genomic technologies"

THEME 3: COLLABORATION

Collaboration, a unifying theme of this report, is necessary for the effective promotion and implementation of genomics and reaching consensus on ELSIs relevant to these activities. Genomic work is generally organized within individual institutions or countries, but the work is often implemented and conducted more efficiently, and the information generated is more useful, if larger collaborations are established. Examples of successful projects may be found in Annex 3. Commitments at high levels to collaborative initiatives, with the involvement of governments, research funding agencies, and others, can reduce expenses and expedite the growth and use of new knowledge. In contrast, efforts by individual organizations or countries can be fragmented and/or limited in uptake if they are not supported by all relevant parties.

Goal: **Foster commitments to collaborative activities to promote all aspects of national and regional programmes that advance genomics in Member States.**

Recommendations

3.1 WHO should promote international collaborations on genomics by strengthening effective existing collaborative arrangements and by helping form new ones for specific needs.

WHO can support existing productive collaborations and guide the formation of new collaborative

relationships between countries and institutions designed to use genomics to address important health problems. WHO should encourage Member States to participate in these international networks and programmes on genomics, especially to help solve health problems of importance to LMICs. These collaborations might include components from HICs and LMICs and from governmental, academic, and commercial sectors. Researchers from LMICs should be an integral part of the executive and planning teams from concept through to completion (e.g., in contributing to conceptualization, design, conduct, and publication of the research projects) in teams with mutual and respectful exchange of experience and capacity between research collaborators.

3.2 Funding agencies should promote collaborative arrangements and encourage the participation of investigators, health care personnel, and computational experts from a diversity of disciplines to promote the optimal use of new genomic information.

Because of their extensive financial resources and the respect in which they are held in the scientific community, research funding agencies have a strong influence on the development and organization of scientific work and on the behaviour of those who receive support from them. For those reasons, the Science Council strongly recommends that funding agencies work together to build consortia in the health science sector to foster implementation of genomic technologies, especially in LMICs. As one example of how this might occur, the Human Hereditary and Health in Africa (H3Africa) consortium is supported largely through a collaboration between the US National Institutes of Health and the Wellcome Trust to promote the use of genomic technologies in several African countries (see Annex 3).

3.3 Industry, academia, and civil society should collaborate on the use of genomics to help solve important health problems, especially those prevalent in LMICs.

Member States should provide incentives to encourage life scientists in the academic, commercial, and government sectors to collaborate by identifying new opportunities for partnerships. Such approaches should foster symbiotic relationships among the health agencies, academia, capital investors, companies, and the public. Member States should examine current expenditures to seek capital for genomics research and development that could be applied to important national problems.

> **"WHO can support existing productive collaborations and guide the formation of new collaborative relationships between countries and institutions designed to use genomics to address important health problems"**

THEME 4: ETHICAL, LEGAL, AND SOCIAL ISSUES

Much of the information revealed by genomic methods, especially information derived from human genomes, has the potential for misuse: violations of privacy, discrimination affecting employment and insurance, inappropriate financial gain, and cultural disrespect. On the other hand, unduly restrictive rules about the generation, sharing, and use of genomic information can limit the benefits that such information can provide. WHO, other international organizations, and governments should develop sensible rules, technical standards, and policies for data access and ownership that are fair to those who deploy and may benefit or suffer from the uses of genomic information. WHO and other institutions should continue to convene international meetings to provide fair platforms for seeking equity and fairness in the use of genomic technologies.

Goal: **Promote ethical, legal, and equitable use and responsible sharing of information obtained with genomic methods through effective oversight and national and international rules and standards in the practice of genomics.**

Recommendations

4.1 WHO, working through its Genomics Committee, should be the custodian of guidance on how to deal with the ethical and social ramifications of genomics, including the global governance of genomic information.

As the directing and coordinating authority for global health, WHO, in conjunction with Member States and partners, should take a leading role in advocating for and helping to develop appropriate governance for the management of genomic information in the following ways:

- The WHO Genomics Committee should convene discussions by scientists, patient advocates, clinicians, lawyers, ethicists, and others to resolve differences in approaches to ELSIs related to the use of genomics;
- WHO and others, including international professional organizations such as GA4GH, should participate in setting and advocating for data standards around genomic information to include data quality standards and mark-up, genetic nomenclature, variants of interest (VOIs) and variants of concern (VOCs) during outbreaks, and health data coding standards and harmonization;
- WHO should develop policies for the transparent governance of laboratory and data management processes, decision making, responsible data sharing, and integration of ELSIs in genomics, with the involvement of all stakeholders;
- WHO should take the lead in ensuring that ELSIs are included in efforts to build genomic capacity, and in workforce training and development discussed under Theme 2 (Implementation). WHO should identify training needs and develop materials that may be integrated into instructional programmes in genomics or taught in specialized workshops targeting relevant parties;
- WHO should become a facilitator of effective communications about ELSIs related to genomics. In responding to the preceding recommended actions under 4.1, WHO should remain aware of the importance of public involvement in the development of policy and professional practice concerning ELSIs in genomics. The WHO Genomics Committee should periodically examine the methods of communication used for such matters in order to encourage engagement of the public in the relevant discussions.

4.2 WHO should take a leading role in the resolution of debates about policies that govern the attribution of credit for genomics research.

WHO, in collaboration with its Member States, should develop guidelines for time- and subject-appropriate sharing, publication, use, and allocation of credit for genomic data in a manner than respects the needs and rights of both the public and the producers of genomic information. Such guidelines will require:

- Understanding research assessment processes and career/institutional review
- Promoting recognition of the value of the generation and sharing of genomic information
- Recognizing individual, institutional, national, and regional contributions
- Enumerating the additional vulnerabilities and sensitivities in low-resource settings.

WHO recently convened an expert consultation to establish principles for pathogen genome data sharing, in the context of research. A report of that consultation, along with the draft principles, will be published on the WHO website.

4.3 Organizations in Member States, especially funding agencies, academic institutions, and governmental units should be attentive to ELSIs and to efforts being made by WHO and other international bodies to develop solutions to controversies related to genomic ELSIs.

The ethical, legal, and social issues raised by genomics are often grounded in local practices and beliefs, yet they may need international solutions that are responsive to those local issues. To make progress towards harmonious solutions that bring the benefits of genomics to all countries, all countries should attempt to engage organizations

in efforts to define relevant ELSIs and to seek acceptable solutions that function globally.

4.4 WHO should aspire to become the global authority on ELSIs for health-related genomic applications.

WHO, in promoting the expanded use of genomic methods, should emphasize the roles and responsibilities of all those who are organizing, funding, and performing genomics and those who are delivering its products, by adhering to ethical and legal standards in genomics and by addressing issues pertaining to local and cultural sensitivities.

As part of those aspirations, WHO should encourage the development of innovative methods for collecting and sharing genetic data, solving genetic dilemmas, and conducting laboratory research. In addition, WHO should look for new opportunities for the public to participate in the research that leads to scientific discovery and for ways to establish new norms regarding the way outputs of genomics research are managed.

Although these recommendations focus on WHO's role in solving ELSIs related to genomics, many other actors have critical roles to play; their responsibilities should not be underestimated.

"WHO should aspire to become the global authority on ELSIs for health-related genomic applications"

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ANNEX 1. METHODOLOGY, WORKSHOPS, AND PARTICIPANTS

Conflict of interest. Each Science Council member was required to complete a WHO declaration of interest form and his/her appointment by the WHO Director-General as a Council member was subject to the WHO Secretariat having evaluated the completed declaration of interest form and determining that his/her participation would not give rise to a real, potential, or perceived conflict of interest. This remains true for the initial appointment as well as the ongoing work being performed by the Council members. These recommendations were devised solely by Council members. Any outside input remained as advice only.

Selection of topic. In April 2021, the WHO Science Council identified genomics as the focus of its first report to the Director-General, given the significant implications of genomics for public health and the broad applications across health and disease states and throughout the human lifespan.

Consultations. A series of consultations[1] was conducted May–October 2021, which focused on developing the workshop objectives and content.

Workshop series. The Science Council held three workshops to better understand the roles of genomics globally and to collect information to inform this report.

Workshop #1 was held on 5 November 2021 and focused on understanding the benefits of genomics. Key questions included:

- What are the genomic technologies and health applications that need to be included?
- What are the direct and indirect benefits (e.g., economic, educational, agricultural, etc.) beyond health?
- What are the potential pitfalls and lessons learned from case studies of specific applications?
- What are the major initiatives designed to promote the use of genomics in LMICs?

The workshop opened with keynote presentations on the history, methods, and use of genomics and a genomics perspective from a LMIC. These were followed by presentations on the applications and benefits of genomics, including insights from WHO meetings on COVID-19; pathogen-focused genomics; human genomics in health care; entomology; botany and economics. Presentations were made by representatives of H3Africa, H3ECaribbean, and industry. The second session focused on how genomics can be helpful for the health of people in LMICs; focusing on infectious diseases, oncology, haematology, congenital conditions and foetal DNA, rare genetic diseases, and genetics of single gene and multifactorial disorders.

Workshop #2 was held on 18 November 2021 and focused on the technical and economic challenges in implementation of genomics. Key questions included:

- How can LMICs initiate and expand the use of genomics technologies?
- What are the requirements for implementation, including funding, technical expertise, equipment and reagents, access to digital resources, etc.?
- What are the mechanisms successfully used and lessons learned from LMICs that have already implemented and expanded genomics technologies?

[1] https://www.who.int/news-room/events/detail/2021/11/05/default-calendar/who-science-council-workshop-series-accelerating-access-to-genomic-technologies-for-global-health

The first session focused on requirements for the implementation of genomic technologies, with keynote presentations on the use of genomic technologies in India and China. Next, perspectives on the requirements for implementation were presented, including equipment and sequencing, pipelines, infrastructure and capacity-building, education and training, and financing. This session concluded with a panel from industry. The second session focused on genomics initiatives, with speakers from different regions.

Workshop #3 was held on 5 December 2021 and focused on understanding the historical, ethical, legal, and regulatory issues to be considered in the application of genomics, including in LMICs. Key questions included:

- What are the lessons learned from the use of genetic technologies in medicine and public health?
- Can we ensure equitable access to genomic technologies and fair sharing of the benefits arising from the use of genomic data?
- What ethical, legal, and social issues need to be recognized and responsibly handled in using genomics?
- What are the relevant regulatory issues at national and international levels?
- What are effective, ethical, and equitable approaches to data sharing?

The workshop opened with keynote presentations on the history and framing of ethical considerations for genomics and for governance. Presentations addressed methods of sample collection, consent and custodianship, community engagement, and general considerations on intellectual property. Speakers working in LMICs shared their perspectives on international networks and biomedical research systems. Generating data and the need for standards, terminology, accuracy, and rules for storage and perspectives on data access and sharing were presented. The final session included perspectives on funding to decrease health disparities; an indigenous perspective on genomics from Canada; and legislation to prevent the misuse of genetic information.

Participants

Workshop #1

Dr Vijay Chandru

Professor Tulio de Oliveira

Professor Geoffrey Ginsburg

Professor Claudia Gonzaga-Jauregui

Dr Peter Goodhand

Dr Glenda Gray

Dr Eric Green

Professor Julie Makani

Dr Daniel Masiga

Professor Funmi Olopade

Dr Tomlin Paul

Professor Michele Ramsay

Professor Jeffrey Sachs

Professor Lavinia Schuler-Faccini

Dr Oluwaseyi Shorinola

Professor Vorasuk Shotelersuk

Dr Marilda Siqueira

Professor Ambroise Wonkam

Dr Maria Caterina Zambon

Workshop #2

Professor Ahmad Abou Tayoun

Mr James Brayer

Professor Iscia Cendes-Lopez

Professor Vajira Dissanayake

Dr Maurice Exner

Dr Philip Febbo

Dr George Gao

Professor Christian Happi

Dr Madhuri Hegde

Professor Dhavendra Kumar

Professor Pui-Yan Kwok

Professor Partha Majumder

Professor Nicola Mulder

Professor Prasit Palittapongarnpim

Dr Charles Rotimi

Dr Herawati Sudoyo

Dr Anita Suresh

Dr Huanming Yang

Professor Soha Yazbek

Workshop #3

Professor Gordon Awandare

Professor Zilfalil Bin Alwi

Dr Ewan Birney

Dr Guy Cochrane

Dr Jantina de Vries

Professor Jayati Ghosh

Professor Yann Joly

Dr Marie-Paule Kieny

Professor Bartha Knoppers

Dr Jessica Kolopenuk

Dr Sebastian Maurer-Stroh

Professor Keymanthri Moodley

Dr William Pewen

Professor Jacob Sherkow

Dr Paulina Tindana

ANNEX 2. RECOMMENDED ACTIONS FOR STAKEHOLDERS

Stakeholder	Promotion	Implementation	Collaboration	Ethical, legal, and social issues (ELSIs)
WHO	Advocate for the expanded use of genomics in Member States Promote affordable access to genomic technologies Persuade Member States; commercial, non-commercial, academic, and other organizations of the benefits of genomics Disseminate information (e.g., advocacy toolkit; educational programmes; opportunities to integrate in other programmes; successful advocacy programmes and technical implementation guides) to Member States Establish a Genomics Committee to perform tasks outlined in report and to evaluate progress made and planned activities	Provide expert advice about strategic plans for implementation and expansion (e.g., implementation guide, inventorying of genomics capacity) Evaluate the business case for investment in genomics in individual countries or regions Genomics committee should convene discussions with organizations in the commercial sector regarding approaches to make their products affordable in LMICs	Promote international collaborations on genomics by strengthening existing ones and helping to form new ones Encourage Member States to participate in international networks and programmes on genomics, to help solve important health problems, especially those prevalent in LMICs	Be the custodian of guidance on how to deal with ethical and social ramifications of genomics WHO Genomics Committee should convene discussions on ELSIs regarding genomics to resolve differences Participate in setting and advocating for data standards around genomic information Develop policies for governance of laboratory and data management Ensure that ELSIs are included in efforts to build genomic capacity, especially in training programmes Take a leading role in the resolution of debates about attribution and credit for genomics research

Stakeholder	Promotion	Implementation	Collaboration	Ethical, legal, and social issues (ELSIs)
WHO				In collaboration with Member States, develop guidelines for data sharing, publication, use and allocation of credit for genomic data Become the global authority on ELSIs for health-related genomic applications
Member States	Develop and conduct advocacy programmes that support the adoption or expansion of genomics Encourage Ministries of Finance, Education, Health, Science and Technology to coordinate advocacy efforts to promote the use of genomics	Establish national programmes for building or expanding genomic capabilities or join regional programmes Identify priority areas for implementation according to public health, medical, and societal needs Ensure sustainable funding for capacity-building, infrastructure development and cost-effective programmes Develop and execute plans to enhance the training of the genomics workforce, including in strategic planning, and assess workforce annually in report to Genomics Committee	Participate in international networks and programmes on genomics, to help solve important health problems, especially those prevalent in LMICs Provide incentives to encourage life scientists in the academic, commercial and government sectors to collaborate by identifying new opportunities for partnerships Foster symbiotic relationships among health agencies, academia, capital investors, companies, and the public	Engage relevant organizations in efforts to define relevant ELSIs and seek acceptable solutions that function globally Be aware of efforts being made by WHO and other international bodies to develop solutions to controversies related to ELSIs Engage organizations in efforts to define ELSIs and seek acceptable solutions that function globally

Stakeholder	Promotion	Implementation	Collaboration	Ethical, legal, and social issues (ELSIs)
Member States		Integrate genomics into undergraduate, medical, and nursing educational programmes. Incorporate genomics into clinical practice through programmes in genetic counselling Increase the understanding of genomics by the public		
Academia, funding agencies, and professional societies in medicine, public health, and bio-informatics	Develop and make widely available information about the uses and benefits of genomics	Develop and execute plans to enhance the training of the genomics workforce Integrate genomics into undergraduate, medical, and nursing educational programmes. Incorporate genomics into clinical practice through programmes in genetic counselling Increase the understanding of genomics by the public	Collaborate on the use of genomics to help solve important health problems, especially those prevalent in LMICs **To funding agencies:** Promote collaborative arrangements and encourage participation of investigators, health care personnel and computational experts to promote the optimal use of new genomic information	Be aware of efforts being made by WHO and other international bodies to develop solutions to controversies related to ELSIs
Industry	Develop and make widely available information about the uses and benefits of genomics	Foster the growth of genomics and capacity-building Engage in WHO meeting(s) that will be convened on making genomics affordable	Collaborate on the use of genomics to help solve important health problems, especially those prevalent in LMICs	Engage relevant organizations in efforts to define ELSIs and seek acceptable solutions that function globally

Stakeholder	Promotion	Implementation	Collaboration	Ethical, legal, and social issues (ELSIs)
Industry		Establish and contribute to an International Genomics Affiliates Fund to support training of the genomics workforce		Be aware of efforts being made by WHO and other international bodies to develop solutions to ELSIs
NGOs	Develop and make widely available information about the uses and benefits of genomics	Develop and execute plans to enhance the training of the genomics workforce Increase the understanding of genomics by the public	Collaborate on the use of genomics to help solve important health problems, especially those prevalent in LMICs	Engage relevant organizations in efforts to define ELSIs and seek acceptable solutions that function globally Be aware of efforts being made by WHO and other international bodies to develop solutions to ELSIs
Regional organ-izations	Facilitate and support the promotion of genomics	Facilitate and support Member States in their efforts	Facilitate and support collaboration on the use of genomics to help solve important health issues, especially those prevalent in LMICs	Facilitate and support good practices

ANNEX 3. EXAMPLES OF ORGANIZATIONS, NETWORKS, AND INITIATIVES ADVANCING GENOMICS

RESOURCES

Accomplishments in the application of genomics to medicine

https://www.genome.gov/health/Genomics-and-Medicine/accomplishments

This website is a list of publications selected by the US National Human Genomics Institute Working Group on Genomic Medicine, the basis for an annual publication on key advances in the application of genomics to medicine.

Catalogue of global genomic data initiatives

https://www.ga4gh.org/community/catalogue/#{%22cat%22:{%22text%22:%22%22,%22page%22:%220%22,%22category%22:{},%22initiative_type%22:{},%22disease_area%22:{},%22data_type%22:{},%22geographical_region%22:{},%22function_role%22:{}}}

This catalogue identifies global resources for sharing clinical and genomic data.

Catalogue of global genomics in medicine initiatives

https://www.genomicspolicy.org/catalogue-introduction

This catalogue describes projects to establish genomics in many countries.

WHO Science Council

https://www.who.int/groups/science-council

Additional electronic resources may be found on the WHO Science Council website and/or the anticipated Genomics Committee website. Thus far, we have commissioned two case studies – one on "Pathogen Data Hubs" by Dr Guy Cochrane and one on "Genetic Discrimination – Challenges and Considerations in a Global Context" by Mr Hanshi Liu, Ms Katherine Cheung, and Dr Yann Joly.

ORGANIZATIONS, NETWORKS, AND INITIATIVES PROMOTING GENOMICS

The programs below promote genomics through a variety of means, including advocacy, implementation, education and training, and collaboration.

ADVOCATING FOR GLOBAL POLICIES AND STANDARDS

Global Alliance for Global Health (GA4GH)

https://www.ga4gh.org/

GA4GH is an international, non-profit alliance formed in 2013 to enable data sharing for the benefit of global health. This is achieved through policy-framing, technical standard setting. and responsible genomic data sharing. The GA4GH community includes more than 600 leading organizations working in healthcare, research, patient advocacy, life science, and information technology and brings this community together to create frameworks and standards to enable and promote the responsible, voluntary, and secure sharing of genomic and health-related data.

Public Policy Projects (PPP)

https://publicpolicyprojects.com/about-ppp/

PPP is an independent policy institute committed to global public policy reform. Its Global Genomics Programme focuses on how collaboration can aid in delivering the benefits of genomics through international collaborative efforts.

IMPLEMENTATION

Brazilian Initiative on Precision Medicine (BIPMed)

https://bipmed.org/

The BIPMed software platform is the first of its kind in Latin America and aims to offer public access to genomic and phenotypic data to be used globally.

Data Hubs

https://www.covid19dataportal.org/the-european-covid-19-data-platform

"Data Hubs" are a system built and maintained at EMBL's European Bioinformatics Institute in collaboration with a number of European public health, disease expert and technical institutions. Data Hubs are used broadly for collaborative data operations across diseases and pathogens and provide a configurable environment for such functions as data sharing, validation, processing and analysis, visualisation, and publication.

Global Genomic Medicine Collaborative (G2MC)

https://g2mc.org/

G2MC is an independent non-profit charitable organization that was started as an 'action collaborative' in the US National Academies of Medicine with support from the US National Institutes of Health. G2MC seeks to advance the implementation of genomics in clinical care. Its specific objectives are to identify opportunities to foster global collaboration: to demonstrate value and the effective use of genomics in medicine; and to establish multinational collaboration on education and workforce development, evidence generation, and policy and regulatory issues.

Genetic Discrimination Observatory (GDO)

https://gdo.global/en

The Genetic Discrimination Observatory is a network of stakeholders dedicated to researching and preventing discrimination based on genomic and other omic data worldwide.

EDUCATION AND TRAINING

Indo-UK Genetic Education Forum (UKIGMA)

https://www.genomicmedicine.org/uk-india-genomic-medicine-alliance-ukigma/

The model of the Indo-UK Genetic Education Forum, organized by the UK-India Genomic Medicine Alliance (UKIGMA), has promoted genomic applications in South Asia and organized seminars, workshops and conferences targeted at specialist workforce, post-graduate courses, undergraduate curriculum development and the adult/public health education. This led to the Global Consortium for Genomic Education, led by the Human Genome Organization, which is committed to genomic education and training.

Global Consortium for Genomic Education

https://www.genomicmedicine.org/global-consortium-genomic-education/#:~:text=The%20Global%20Consortium%20for%20Genomic%20Education%20(GC4GE)%20is%20a%20major,with%20a%20particular%20focus%20on

The HUGO Education Committee has set out an educational agenda that is specifically targeted at LMICs.

Eastern Africa Network for Bioinformatics Training (EANBiT)

https://eanbit.icipe.org/

The Eastern Africa Network for Bioinformatics Training is a collaborative network of three universities and four research institutes in Kenya, United Republic of Tanzania, and Uganda supported by the Fogarty International Center of the US National Institutes of Health under the H3Africa programme. The core objective is to strengthen the application of Bioinformatics in Biosciences Research through individual training, research mentorship and enhancing institutional capacity in East and Central Africa.

Summer Internships for Indigenous Peoples in Genomics Canada (SING Canada)

https://indigenoussts.com/sing-canada/sing-canada-2022/

SING Canada is an initiative associated with the Indigenous Science, Technology, and Society Research Training Program at the University of Alberta to build indigenous capacity and scientific literacy in genomics, bioinformatics and indigenous and decolonial bioethics

CONSORTIA AND NETWORKS

All of Us Research Program

https://allofus.nih.gov/

The All of Us Research Program is an effort by the US National Institutes of Health to gather health data from one million or more people living in the United States. Nearly 100,000 whole genome sequences, diverse with respect to race, ethnicity, age, region of country, gender identity, sexual orientation, socioeconomic status, education, disability, health status, became available as of March 2022.

Severe Acute Respiratory Infections Network (SARInet)

https://www.sarinet.org/en/explore-sarinet

Pan American Health Organization (PAHO) created SARInet to build capacity in the Americas for surveillance and laboratory diagnosis of influenza and other respiratory viruses This network is a model of collaboration for the introduction of genomics among countries in the Americas.

Genomics Thailand

https://genomicsthailand.com/Genomic/about

A collaborative network supported by the government of Thailand to enable disease prevention and treatment that takes into account people's individual variations in genes, environment and lifestyles.

Global Globin Network (GGN)

https://www.humanvariomeproject.org/gg2020/index.html

The Global Globin Network of the Human Variome Project and Global Variome is a network that is working with LMICs to integrate genomic medicine into their health care systems. GGN specifically focuses on haemoglobinopathies, which cause significant morbidity and mortality globally. GGN seeks to apply recent developments in human genomics involving the systematic collection and sharing of variation data to fighting haemoglobinopathies (notably thalassaemias and sickle cell disease) in LMICs.

Human Hereditary and Health in Africa (H3Africa)

https://h3africa.org/

The Human Hereditary and Health in Africa consortium is funded by the Wellcome Trust, US National Institutes of Health, and Science for Africa Foundation. H3Africa empowers researchers in 30 African nations to be competitive in genomic sciences, establishes and nurtures collaboration among researchers on their home continent and generates unique data that could be used to improve both local and global health.

Human Heredity, Environment, and Health in the Caribbean (H3ECaribbean)

https://www.jaccri.org/h3ec

The Human Heredity, Environment, and Health in the Caribbean Initiative was launched in 2021 to build the health infrastructure needed to investigate genomic, environmental, and social influences on the aetiology of chronic disease in the region and to ensure inclusion of persons from the Caribbean in global health research.

Hong Kong Genome Project

https://www.fhb.gov.hk/en/press_and_publications/otherinfo/200300_genomic/index.html

The Hong Kong Genome Project is the first large-scale genome sequencing project in Hong Kong aiming to sequence 50,000 genomes in six years. The strategic decision making for this programme is outlined above.

Sickle in Africa Consortium

https://www.sickleinafrica.org/

Sickle in Africa is a consortium that aims to facilitate research in sickle cell disease and promote the translation of research into healthcare and health outcomes.

The Center for Genomic Discovery

https://www.mbru.ac.ae/research/the-center-for-genomic-discovery/

The Center for Genomic Discovery creates a scientific and clinical interdisciplinary ecosystem across multiple institutions in Dubai with goals of diagnosing and treating patients with genetic disorders, enhancing local genomics research, and providing scientific training.

World Health Organization

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