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Preparedness of public health laboratories for respiratory infectious diseases – EU/EEA country perspectives on lessons learned from the COVID-19 pandemic

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Abbreviations

EEA	European Economic Area
EU	European Union
GDPR	General Data Protection Regulation
PHL	Public Health Laboratories
PPE	Personal Protective Equipment
RT-PCR	Reverse Transcription Polymerase Chain Reaction
RT-LAMP	Reverse transcription loop-mediated isothermal amplification
SOP	Standard Operating Procedure
WHO	World Health Organization

Key findings

During the COVID-19 pandemic, public health laboratories (PHLs) in EU/EEA countries faced intense pressure due to high levels of demand and limited capacity and resources. They faced challenges in staffing laboratories with sufficiently trained staff and implementing new digital infrastructure to support genomic surveillance. Supply chain and procurement issues led to shortages in key equipment, and laboratories struggled to keep up with demands in public health surveillance and supporting other types of laboratories.

In response, PHLs increased capacity by hiring and training new staff, building new physical and digital infrastructure, and procured supplies through new procurement schemes and from new sources. PHL activities were supplemented by collaboration across sectors, including drawing on capacity from the military, animal health laboratories and the private sector.

The COVID-19 pandemic led to great advances in genomic surveillance, sequencing capacity, and other techniques such as wastewater surveillance. During the pandemic, PHLs implemented new techniques and methods, and needed to respond rapidly to emerging evidence, including information about variants. Guidelines and standard operating procedures were crucial in informing practice within PHLs and helped spread best practice and improved data quality.

PHLs struggled with data sharing, collaboration and coordination during the pandemic. Collaboration and networks were crucial in addressing some of these challenges. For example, regional networks within countries helped enable improved surveillance, and EU-level and WHO-facilitated collaborations helped improve capacity and communication during the pandemic.

There is an opportunity to learn from the experience of the COVID-19 pandemic to help improve the preparedness of PHLs for future health threats, including balancing the speed, accuracy and quantity of tests that laboratories need to deliver. Information about the types of PHL activities that are most effective to inform decision making at different points in pandemics can support this.

To improve preparedness of PHLs for future respiratory health threats, countries should maintain sufficient PHL capacity during 'peace time' to detect threats and create plans for scaling up capacity during emergencies. They should create coordination mechanisms between PHLs and cross-sectoral stakeholders and address challenges that slow data sharing during emergencies, including enhancing digital infrastructure where needed.

To improve preparedness for future health threats, PHLs will require:

- resources and capacity to support long-term preparedness, and continued support for coordination and data sharing during public health emergencies;
- evidence on 'right-sizing' surveillance activities such as sequencing and PCR testing to inform PHL priorities in future public health emergencies;
- support to maintain the advances made during the pandemic, including in sequencing, genomic surveillance, wastewater surveillance, and training staff in new laboratory techniques;
- enhanced preparedness planning, including how and when to scale up and scale down capacity to meet demands.

Participants from PHLs in EU/EEA countries highlighted EU-level support they thought would help improve preparedness for future respiratory infectious diseases:

- maintaining and, where needed, increasing resources provided to support long-term preparedness where there are gaps in countries;
- collating evidence around best practice related to PHL activities and identifying specific evidence gaps in responding to public health emergencies;
- funding research that fills gaps in understanding how to conduct surveillance that meets the needs of decision makers, and that makes the best use of available resources (e.g. evidence on 'right-sizing' surveillance activities);
- implementing EU-level actions to address supply chain issues, including stock piling and joint procurement;
- conducting EU-wide preparedness exercises to bring stakeholders involved in responding to public health emergencies together, which can help improve communication, coordination and agility during crises;
- clarifying the role that different EU-level actors play in supporting PHL preparedness;
- continuing to build and strengthen networks and collaborations amongst PHLs, other laboratories, and other stakeholders.

Introduction

Infectious diseases can cause significant harm to public health, the economy and society. The World Health Organisation (WHO) has included 'Preparing for epidemics' on their list of urgent health challenges for the next decade [1,2] and ECDC has published several reports on the importance of strengthening pandemic preparedness [3–5]. Moreover, recent disease outbreaks, most notably, the COVID-19 pandemic and recent influenza outbreaks [6,7] have emphasised the need for effective and robust preparedness strategies for respiratory infectious diseases.

Public health laboratories (PHLs) play an important role in the public health system. They are used to enable the detection and characterisation of public health threats, conduct surveillance, and support hospital and diagnostic laboratories, and to conduct mass testing programmes or national seroprevalence studies. Public health laboratories support timely detection of threats and help generate data to inform public health responses. Given the critical role of such laboratories in detecting, monitoring and informing response to public health threats, strengthening their ability to maintain core functions during public health emergencies is vital [8].

This report provides evidence to understand the main hurdles faced by PHLs during the COVID-19 pandemic, the solutions implemented to address these challenges, and the advancements made during the pandemic in the European Union and European Economic Area (EU/EEA) countries. It focuses on experiences of PHLs within EU/EEA countries and aims to inform long-term strategies to improve preparedness of PHLs for health threats caused by respiratory infectious diseases. In this study, PHLs are defined as any laboratory that supports the health of a country's population by providing essential laboratory testing services, conducting surveillance and research, and informing public health responses aimed at preventing, detecting, and controlling diseases and other health threats. We looked at PHLs in EU/EEA countries only, including National Reference Laboratories and other types of PHLs.

Aim and scope of the study

The purpose of this study was to provide evidence to the European Centre for Disease Prevention and Control (ECDC) and other key stakeholders in the public health arena on how to help PHLs be better prepared and more resilient to future public health challenges related to respiratory infectious diseases. The guiding research questions for this study were:

- What were the main challenges PHLs faced during the COVID-19 pandemic?
- What solutions were implemented by PHLs to address these challenges, and what advances were made during the COVID-19 pandemic?
- What was the impact and the implications of the solutions implemented by PHLs?
- What is necessary to sustain the advances made during the COVID-19 pandemic in PHL preparedness?
- How can the lessons learned during the COVID-19 pandemic be used to enhance PHL preparedness for other respiratory infectious diseases (including influenza, RSV and other emerging threats) and potential new pandemics?
- What long term strategies should be developed to ensure PHLs remain resilient and adaptable in the face of future public health threats?

The scope of the study was restricted to PHLs and lessons applicable in EU/EEA countries. The role of PHLs is to deliver timely, reliable services in support of disease control and prevention. Activities that they conduct include reference testing, disease surveillance, population-based interventions, communication with healthcare providers, and emergency response. Other activities that take place outside of PHLs were excluded from the scope of this study, including point of care tests, activities within clinical laboratories, and mobile health laboratories. The study focused broadly on practices, strategies and new technologies that were put in place to respond to countries' needs and address challenges during the COVID-19 pandemic such as new techniques developed in response to COVID-19, new staffing models, and new ways of working.

How to use this report

This report provides the results of the study, triangulating findings from desk research, a survey, interviews and a technical meeting. The report is organised chronologically across three phases of the pandemic: early (when uncertainty was high), middle (when capacity and scaling up were a primary challenge) and end (moving forward from the pandemic). Each section explores the key challenges faced by laboratories during each phase, along with the solutions that were implemented or proposed in response.

Methods

Rapid evidence assessment

We used a rapid evidence assessment approach to conduct desk research on the challenges that PHLs faced during the COVID-19 pandemic, what solutions were put in place, and lessons that can help improve long-term preparedness. A rapid evidence assessment takes a systematic approach to searching, selecting and extracting information from literature by creating a clear search strategy and implementing inclusion and exclusion criteria in a consistent and reproducible manner. It also allows for prioritisation of articles to provide the best value for the resources available [9].

Data collection

We gathered data from public health authorities across EU/EEA countries, via a survey and interviews. Invitations to participate in interviews were sent to ECDC National Focal Points for Respiratory Viral diseases and invitations to participate in surveys were sent to the following ECDC networks: National Focal Points for Respiratory Viral diseases, National Microbiology Focal Points, Operational Contact Points Microbiology for COVID-19 and/or influenza, in the 30 EU/EEA countries. These participants were asked to select contact points within each country that would have an overall perspective of PHL experience during the pandemic and could provide suggestions on how preparedness in these laboratories can be improved. Participation in these data collection activities is summarised in Table 1 below. All data was collected between November 2024 and March 2025. In this report, we have assigned an anonymous identifier to each interviewee, and we only report the results from the technical meeting and open-text survey responses in aggregate.

Table 1. Summary of data collection activities

Activity	Invitees	Participation	Countries consulted
Interviews	National Focal Points for Respiratory Viral Diseases	14 Interviews conducted	Belgium, Croatia, Denmark, Finland, Germany, Iceland, Italy, Lithuania, Luxembourg, Netherlands, Norway, Portugal, Slovenia, Sweden
Surveys	National Focal Points for Respiratory Viral Diseases, Microbiology Focal Points (MFPs), Operational Contact Points for COVID-19/influenza	32 Survey responses from 24 countries	24 EU/EEA countries responded; Austria (n=2), Belgium (n=1), Bulgaria (n=1), Croatia (n=1), Czech Republic (n=1), Denmark (n=1), Estonia (n=1), Finland (n=1), Germany (n=1), Greece (n=2), Iceland (n=1), Ireland (n=2), Italy (n=1), Lithuania (n=2), Luxemburg (n=1), Malta (n=1), Netherland (n=1), Norway (n=2), Republic of Cyprus (n=3), Romania (n=2), Slovak Republic (n=1), Slovenia (n=1), Spain (n=1), Sweden (n=1)
Technical Meeting	Experts EU/EEA countries and EU agencies (ECDC, European Food Safety Authority, European Medicines Agency, Health Emergency Preparedness and Response Authority, SANTE.B.2,)	58 Participants: Representatives from 28 countries + five EU agencies + two Advisory Board members	Belgium (n=2), Bulgaria (n=1), Croatia (n=2), Cyprus (n=1), Denmark (n=2), Estonia (n=1), Finland (n=1), France (n=2), Germany (n=1), Greece (n=2), Hungary (n=2), Iceland (n=1), Ireland (n=2), Latvia (n=1), Lithuania (n=1), Luxembourg (n=2), Netherlands (n=2), Norway (n=1), Poland (n=2), Portugal (n=2), Romania (n=2), Slovak Republic (n=2), Slovenia (n=1), Sweden (n=2)

Technical meeting

Following the synthesis of data from interviews and surveys, a half day ECDC virtual technical meeting with 58 participants was convened with representatives from EU/EEA countries and from ECDC, the European Food Safety Authority, the European Medicines Agency, the Health Emergency Preparedness and Response Authority and the Directorate-General for Health and Food Safety. We presented our findings from the literature review, interviews and surveys for feedback and refinement from country representatives. Prior to the meeting, participants were provided with material which summarised the findings from the mapping study consisting of the literature review, interviews and survey.

During the meeting, we facilitated a discussion of challenges and solutions in PHLs during the COVID-19 pandemic, lessons learned, and what can be done to improve preparedness for future health threats caused by respiratory infectious diseases. We also facilitated a discussion on how EU institutions can support countries in improving preparedness in PHLs. Detailed notes of the plenary and small-group discussions were taken by researchers and facilitators.

Analysis

Results from the desk research were analysed by research question, using an extraction template (Annex 1). A coding framework (Annex 5) was developed to analyse the interview notes, after reading through a sample of the data to familiarise ourselves with the themes. MAXQDA, a qualitative analysis software, was used to systematically code free text. Quantitative questions within the survey were analysed using descriptive statistics, and graphs were produced to visualise data collected, including differences between EU/EEA countries.

We then analysed the detailed notes taken during the technical meeting, and triangulated evidence from across the whole study to provide clear answers to each research question and reflect on the diversity and strength of the evidence collected.

Limitations

The scope of this study was centred around the experiences of PHLs in EU/EEA countries during the COVID-19 pandemic. While this focus was essential for understanding the specific challenges encountered and the solutions or lessons learned by PHLs, it inherently presented limitations. PHLs are deeply interconnected with broader public health systems. Consequently, certain aspects of the pandemic response that are adjacent to the functioning of PHLs, but do not directly feed into the PHL system, may not have been fully considered within this study (e.g. point of care testing and clinical laboratory activity without involvement of PHLs).

To maintain a manageable scope, the study focused exclusively on the experiences of PHLs in EU/EEA countries. While the aim was to derive lessons applicable to EU/EEA countries, this geographical limitation meant that insights from countries outside this region were not included. Despite operating within different health systems, non-EU/EEA countries might have offered valuable lessons that could be applicable to the European context.

While we established clear and transparent prioritisation criteria that balanced breadth and depth of the rapid evidence assessment, prioritisation may have restricted the comprehensiveness of the findings and the ability to capture the full spectrum of challenges and solutions experienced by PHLs during the COVID-19 pandemic. To address this limitation, the results from the assessment were complemented by a technical meeting and consultations.

The sampling for interviews, surveys and the technical meeting was focused on specific roles within PHLs, which may not have captured the full diversity of viewpoints and experiences across different roles. People in other roles may have different perspectives on the challenges faced and solutions implemented. Additionally, there was potential bias inherent in self-reporting, as participants may have unintentionally or intentionally misrepresented their experiences. This bias was mitigated by incorporating findings from the literature, providing a more balanced and comprehensive understanding of the PHLs' experiences during the COVID-19 pandemic, although the literature may also be limited in what challenges are discussed and published. In the future, gathering the views of other experts in preparedness and resilience outside of PHLs, including from other sectors, may also be informative in generating lessons for PHLs.

Results

Applying the exclusion and inclusion criteria resulted in a total of 149 articles from both academic and grey literature for further prioritisation. In total, we conducted 14 interviews, collected 32 survey responses from 24 countries and 58 attendees took part in the technical meeting.

Experiences of public health laboratories early in the COVID-19 pandemic

This chapter presents the experiences of PHLs during the early stages of the COVID-19 pandemic, focusing on their evolving roles, communication demands, and the development of testing protocols. The initial phase of the pandemic was marked by significant uncertainty surrounding the transmission dynamics and epidemiology of SARS-CoV-2, which complicated efforts to monitor and respond effectively. Coupled with this uncertainty were significantly increased demands on PHLs, particularly around testing.

Navigating uncertainty and changing roles early in the pandemic

Scientific gaps and uncertainty made it challenging for public health laboratories to operate and make decisions early in the pandemic

The initial phase of the pandemic was characterised by uncertainty, particularly regarding transmission dynamics, virological characteristics and the epidemiology of the SARS-CoV-2 virus, which made it challenging to monitor and respond to the pandemic [10]. As is often the case with novel pathogens, the limited availability of scientific information about SARS-CoV-2 contributed to delays in implementing effective infection control measures. Several participants from the technical meeting highlighted that, in the initial stages of the pandemic, information about the severity of COVID-19, the infectivity of the virus and the biosafety level they needed to work at, was limited. Participants in the technical meeting also noted that as new information emerged about the microbiology and epidemiology of SARS-CoV-2, guidelines were adapted to reflect new knowledge, including from research evidence and pre-prints. Participants commented that PHLs were expected to respond rapidly to guidance and demands that were continuously evolving, which was challenging. Some reflected that the reactive nature of response, especially early in the pandemic, contributed to pressure on PHLs.

Several factors contributed to limited understanding of the virus in the early stages of the pandemic. For example, participants in the technical meeting noted that information from sentinel surveillance was limited due to the reduced use of in-person primary care services which disrupted this source of information for surveillance. A study of six sentinel sites in EU countries found that sentinel surveillance was disrupted due to altered patient pathways and less patients attending primary care. Portugal and Spain adapted to this change by temporarily stopping sentinel surveillance for all respiratory infections during the initial pandemic wave due to restructured patient pathways and national testing strategies that bypassed primary care [11]. Participants from the technical meeting also noted that differences in surveillance efforts and data availability/accessibility between countries contributed to challenges in understanding the population dynamics of the virus.

During the pandemic, public health laboratories had additional responsibilities which added to their workload.

The pandemic pushed many PHLs to adopt new and expanded roles outside of those traditionally held by PHLs during non-pandemic times (e.g. providing expert advice, national standards and protocols, identifying and characterising pathogens). These additional tasks included expanding PHLs' role in supporting diagnostic capabilities, driven in part by significant demands on laboratory infrastructure to scale up PCR testing capacities, and providing quality assuring laboratory processes and results [12]. expert advice, national standards and protocols, identifying and characterising pathogens). Participants in the study indicated that PHLs struggled to find the capacity to complete all of the roles that were delegated to them early in the COVID-19 pandemic.

Communication expectations and the politicisation of the COVID-19 pandemic created new challenges for stakeholders from public health laboratories

During the early stages of the pandemic, PHLs' role in external communications expanded. Technical meeting participants reported that laboratory staff faced an increased expectation to communicate with and answer questions from elected officials and the public (through media outlets), who sometimes had limited understanding of virology. For example, PHL staff communicated about how the virus was being transmitted and educated the public on technical terms such as Ct values [1]. Participants noted this was particularly challenging in the context of waning trust in public health institutions and science, which intensified during the pandemic. At the same time,

[1] Ct values refer to cycle thresholds which can provide a rough estimate of viral load in a PCR test.

PHLs were also communicating extensively with other experts to exchange knowledge about the virus and best practice for testing and analysis, which added to the communication burden they faced.

Many participants highlighted the importance of engaging with the public and public officials to communicate about key public health insights and messages. However, participants noted the importance of having a well-planned communication strategy to prevent PHLs from being too reactive in their communications approach, and to protect against PHLs spending too much time and resources on this activity in comparison to other obligations. ECDC also identified risk communication activities as a key lesson from the COVID-19 pandemic, particularly the need for public health institutes to communicate complex scientific findings clearly to policy makers and the public [13]. While it is not clear from this study what the correct level of communication would be for PHLs during future public health emergencies, the impact of heightened expectations around communication should be considered in future pandemics and relevant individuals in the PHLs should receive adequate training in time to cope with the demands.

The role of public health laboratories also changed due to the degree of politicisation of public health activities during the COVID-19 pandemic, with some even reporting threats of violence against laboratory staff. Several participants suggested that mass testing of the general population went on for longer than necessary, and that the volume of confirmatory PCR tests requested during the pandemic created additional pressures on PHLs.

Supporting public health laboratory activities early in the pandemic

PHLs need to develop effective tests and understand their performance early in public health emergencies.

Early in the pandemic, PHLs needed effective tools to better understand the virus and track its spread. However, tools and testing strategies varied in performance (accuracy and specificity), and laboratory staff faced challenges in developing effective assays and evaluating the performance of existing techniques. For example, positive SARS-CoV-2 samples (and samples positive for particular variants) were critical for assay validation, but many PHLs struggled to access these samples early in the pandemic despite national and international programmes like EVAg (European Virus Archive Global) designed to provide access [14,15]. This hindered the ability of PHL staff to validate assays quickly at a time when effective detection tools were crucial to responding to the pandemic.

Countries implemented a number of measures aimed to further assess, improve the quality of and standardise laboratory methods, which were supported by PHLs. For example, external quality assessment schemes allowed laboratories to obtain certifications to test for SARS-CoV-2 and evaluate their performance [16–19]. Research studies also helped compare the sensitivity of different assays and methods [20]. These comparative evaluations were crucial for establishing best practice and determining the most appropriate method for different testing scenarios.

Developing standard operating procedures and standardised methods support PHL preparedness

PHL staff needed to develop standard operating procedures (SOPs) and standardised methods during the pandemic and ensure that these met best practice based on information available at the time. The development of SOPs for specimen handling, personal protective equipment (PPE) use, emergency scenarios, and new techniques was important to ensure safety and consistency [21]. In the early stage of the pandemic, some countries leveraged existing plans and SOPs from other infectious diseases to develop testing guidelines, including specimen collection, transportation, and safety concerns [22]. However, protocols needed to be updated as new information about the SARS-CoV-2 virus emerged.

International guidelines and protocols helped PHL staff in EU/EEA countries design and implement these procedures, for example, WHO and ECDC published guidelines and protocols for Reverse Transcription Polymerase Chain Reaction (RT-PCR) and other methodologies [23–25], which aimed to produce consistent and reliable results across different geographical areas. In the technical meeting, participants discussed the importance of WHO and ECDC material to help inform their approaches.

Meeting demands during the COVID-19 pandemic

This chapter examines how PHLs met demands during the COVID-19 pandemic, touching on the infrastructure and capacities that were required, the challenges staff faced and some solutions that were implemented or proposed. Firstly, we discuss the significant pressures PHLs came under during the pandemic as well as the resource constraints and strain on existing resources. Second, we look at workforce related challenges and how these have or could be addressed. Thirdly, we examine infrastructure constraints in light of rapidly expanding testing, and finally issues relating to and solutions of digital infrastructure.

Resolving resource and infrastructure challenges and scaling up capacity

Resource constraints during the COVID-19 pandemic made it challenging for PHLs to meet high levels of demand.

During the pandemic, PHLs faced capacity constraints and struggled to meet surging demand for laboratory services, according to interviewees and technical meeting attendees**.** Laboratories often lacked sufficient equipment, personnel, and other resources, and faced challenges recruiting new staff, acquiring laboratory equipment and facilities, establishing sampling sites, and obtaining test kits and swabs [26]. Interviewees reported that high levels of demand put strain on logistics around sample collection, transport and storage, as well as the training of new recruits. The survey also found that two of the most frequently identified challenges for public health laboratories was the high demand for laboratory services (selected by 91% of participants) and challenges with supply chains and equipment (selected by 75%). The scarcity of essential supplies, space and materials had a cascading effect on laboratory operations, slowing down laboratory processes.

While public health emergencies can be expected to raise pressure and contribute to resource constraints in PHLs, several features of the COVID-19 pandemic exacerbated these including increased demand for communication with the public; supporting activities in hospital and diagnostic laboratories; supporting mass testing, and the volume of sequencing required.

To help address these pressures in future public health emergencies, workshop participants identified a need to understand which testing strategies were effective and what volumes of sequencing would be appropriate to provide insights to inform public health activities at different stages of a public health. As maintaining high levels of capacity is resource intensive, participants also noted the need for clarity on when to downscale testing capacity. Many participants expressed the hope that EU-level action would be helpful in filling knowledge gaps that are shared by PHLs across many countries. Specific challenges relating to resourcing, staffing, infrastructure and equipment are discussed in more detail below.

Workforce challenges and shortages affected public health laboratories during COVID-19 and continue to influence preparedness for future pandemics.

Workforce capacity, hiring and ways of working

Many laboratories reported insufficient staff to handle the increased testing demands [15], and staffing and capacity constraints were also some of the most frequently identified challenges in our survey. Workforce capacity issues were intensified by factors such as illness and quarantine requirements, as well as stress, fatigue and limited support systems for staff [21]. During the COVID-19 pandemic, laboratories and public health institutions implemented various strategies to mitigate these issues. Some laboratories outsourced certain tasks to other institutions or departments to manage workloads better [27], and shift working was often employed to increase capacity and prevent the virus spreading among staff [28]. This approach can be successful in increasing and maintaining capacity; however, it can lead to additional stress burnout (discussed in more detail below)[21]. Some countries had database and rosters of trained laboratory technicians who could perform PCR testing in preparation for surges [22].

Interviewees and technical meeting participants outlined several ways to enhance workforce capacity. These included hiring new staff (which was also noted as a common solution among PHLs from survey respondents), speeding up hiring and training processes, reassigning personnel from other areas (e.g. private sector laboratories, academia, military) to PHLs, and implementing shift work. However, interviewees noted that reassigning staff from other departments may disrupt operations in those areas and requires careful consideration of how core services will continue to be delivered during public health emergencies, and whether gaps in capacity in other areas are acceptable.

PHLs also took steps to prioritise essential work to ensure that the most critical tasks were completed by the existing workforce. This involved deciding which tests to conduct and how to allocate scarce resources effectively [21]. In Spain, for example, all suspected cases were initially tested, but later, testing was limited to severe cases and essential groups, such as health workers [11].

Although PHLs hired new staff with additional funding allocated during the pandemic, the long-term sustainability of these hiring measures is unclear [27]. Participants from the technical meeting agreed on the challenges of maintaining capacity during peace time, when the need for continued surveillance must be balanced with the costs of achieving this. Participants noted that many laboratories have seen highly trained workers leave the workforce in the aftermath of the COVID-19 pandemic and attributed this to several factors, including reduced funding (including lapses in funding from European programmes), post-pandemic burnout and trauma among staff (which some participants reported to be leading to high rates of sick leave), and the existence of more attractive and higher-paying jobs elsewhere. This exit from the workforce of highly skilled workers has the potential to create a skill shortage that reduces preparedness for future health emergencies.

To avoid this, participants highlighted the necessity of continued funding for PHLs to enable them to retain trained staff and the need to make PHLs attractive places to work, as well as advocating for long-term staffing strategies to enable staffing to be rapidly scaled up as needed during emergencies.

Skills gaps

Although gaps in the skills and knowledge of laboratory staff was seldom reported by respondents to the survey (19%), the wider literature indicates that this issue likely affected PHL capacity in EU/EEA countries to some extent [29]. A study in 2020 showed that approximately 30% of diagnostic microbiology laboratories awaited availability of commercial tests to guide their efforts in diagnostic assays, due to the lack in expertise in molecular assay development [15]. Additionally, techniques such as reverse transcription loop-mediated isothermal amplification (RT-LAMP) may require specific training for interpretation of results to minimise the risk of false negatives and ensure the quality of test results, given that results are presented by colour (as compared to, for instance, RT-PCR where results are either binary or quantitative) [30,31]. Genomic surveillance also requires higher skill levels and specific expertise in bioinformatics, as processing and analysis of raw pathogen sequence data is more complex and not easily interpretable for non-specialists.

During the technical meeting, several attendees reported that during the pandemic, PHLs had trained both new and existing staff to use new methodologies, platforms and equipment. The literature suggests that, given ongoing developments, continued workforce training might be needed in areas like genomic surveillance, new technologies and the use of integrated data systems [16,29,32]. As well as increasing laboratory capacity, these measures can also help improve safety in laboratories (with robust biosafety management systems and cultures of safety and accountability) [21]. Training and up-skilling staff during the pandemic helped ensure staff were skilled in theoretical principles important to PHLs, practical techniques used in laboratories, and data analysis [33,34].

For example, the WHO Country Office in Türkiye developed a training programme on next-generation sequencing, bioinformatics, and molecular epidemiology in consultation with experts from six WHO regions [35]. ECDC also invested in workforce capacity development programmes across EU and non-EU countries, such as through the European Programme for Intervention Epidemiology Training Fellowship (EPIET), the European Public Health Microbiology Programme (EUPHEM), and the Mediterranean Programme for Intervention Epidemiology Training, to increase the quality and number of trained professionals [13]. ECDC also funded the AURORAE consortium, which provided support and training to microbiology initiatives, including laboratory training, support and standardisation [36]. There have also been examples of establishing call centres and hotlines with laboratory specialists who provided ongoing training and support to laboratory technicians [22]. Other ways that PHL staff adapted to the pandemic included staying informed about emerging technologies and scientific advancements by attending conferences, reading scientific literature, and engaging in professional networks [34].

Workplace wellbeing

The pandemic placed significant mental and physical strain on laboratory personnel. The increased workload, coupled with the high-stakes nature of their tasks and potential exposure to the virus highlighted the need for robust support systems to maintain the wellbeing of staff, who were essential to the pandemic response [21]. Interviewees from public health authorities in EU/EEA countries provided further insight on workforce challenges, highlighting that high testing volumes and the requirement for continuous work around the clock placed significant pressure on existing staff, and made it difficult to hire and provide adequate training for new recruits. Support for the mental and physical wellbeing of workers may include encouraging time off and breaks, mental health support and periodic occupational health follow up [21].

Physical safety was also a concern, as laboratories had to rapidly adapt to new technologies, diagnostic tests, and procedures related to SARS-CoV-2 in the context of significant uncertainty. This adaptation required just-in-time training for personnel, ensuring they were proficient in using and removing personal protective equipment such as FFP2 or powered air-purifying respirators [21]. Aerosol contamination risk was also a concern, particularly with some CRISPR-based diagnostic methods, necessitating the implementation of appropriate safety protocols and training personnel in handling these assays to mitigate this risk [30]. Solutions to safety considerations in the laboratory should be based on a risk assessment and may include secondary barriers (i.e. transmission control barriers), training and standard operating procedures for novel products and techniques [21].

Public health laboratories found new suppliers and solutions during the COVID-19 pandemic to address infrastructure, supply and procurement difficulties.

Physical infrastructure and supplies

Laboratory equipment, disposables and tests were urgently needed during the pandemic, and the pace of development, production, regulatory approval and procurement of these supplies influenced the ability to respond to COVID-19. The COVID-19 pandemic exposed and exacerbated vulnerabilities within global supply chains, significantly impacting the availability and reliability of essential laboratory supplies. Critical shortages were observed in PPE (e.g. gloves, gowns, FFP2, and Powered Air Purifying Respirators), testing reagents, and consumables such as swabs, plasticware, tubes and lysis buffers, alongside difficulties sourcing equipment and consumables for genomic sequencing [21,29]. These shortages posed substantial challenges to maintaining laboratory operations and ensuring public health safety, which was echoed by interviewees who stated that shortages of essential materials were common. Survey participants also agreed that issues with supply chains and equipment was a key challenge faced by PHLs. The increase in demand as well as disruptions in manufacturing meant that laboratories had to be vigilant in ensuring that all PPE met necessary safety standards, consider reuse procedures, and face the risk of counterfeit materials entering the supply chain [21]. Several participants in the technical meeting noted that procurement challenges were particularly acute for smaller countries, as companies preferred to supply larger quantities of materials to bigger countries.

In response to these challenges, laboratories in EU/EEA countries explored alternative suppliers, created materials in-house, and collaborated with external partners. Some innovative solutions that might inform future approaches included expanding manufacturing capacity through 3D printing, public-private partnerships and enhancing PHLs' ability to produce and validate diagnostic and laboratory tests in-house. Several country representatives reported innovative solutions, including Denmark, which established modular laboratories (portacabin style laboratory units) capable of processing 100 000 tests per day; Lithuania, where PHLs collaborated with veterinary and private laboratories; and several countries implemented automated processes and robots to process samples and handle large-scale diagnostic testing. Centralised purchasing and allocation systems were also established to try to manage shortages, as well as stockpiling to build resilience and protect against vulnerable just-in-time supply chains.

During the technical meeting, participants from PHLs in EU/EEA countries reflected on ways to address supply chain challenges. Several participants agreed that interventions in their countries around procurement at national level helped address challenges in lack of supplies. One participant also noted that changes to procurement laws and processes enabled faster procurement of reagents and consumables during the pandemic, although this has since returned to the usual processes. Participants also noted that public-private partnerships worked well to help expand supplies and infrastructure, with one stating that it enabled more rapid scaling up of the number of laboratories involved in testing. However, several participants added the caveat that this required PHLs to take on a time-consuming quality assurance role, which added to pressures. Some participants in the technical meeting also noted the need to improve procurement during peace time in order to prepare for emergency situations. For example, several participants discussed the importance of stockpiling to improve EU preparedness, and one participant suggested more EU-level procurement of equipment that can be applied to multiple different types of laboratory tests depending on the nature of the next pandemic.

Lessons from the COVID-19 pandemic indicate the need for more robust supply chains and more robust laboratory procurement systems [15,21,22]. Once new testing technologies are developed and procured, it is important that regulatory processes move quickly to ensure new technologies can be incorporated into surveillance and diagnostic strategies, which may include emergency use authorisation and other fast-track authorisation programmes [26].

Digital infrastructure

During the pandemic, PHLs needed to store, maintain, and share large volumes of data, and create robust systems to link data from multiple sources. The limited capacity of technical systems, including hardware and data management system limitations, posed significant challenges [29]. Interviewees and technical meeting attendees reported that existing data systems were generally inadequate for handling large volumes of test results, data sharing between partners was slow, manual data entry led to delays, and incompatible IT systems across regions hindered data sharing.

Spreadsheets, though widely used for data handling, were unsuitable for large datasets, collaboration, and continuous storage, and were prone to data corruption [37]. While laboratory management software offered better alternatives, their complexity, time-consuming implementation and maintenance represented difficulties [37]. The need to build new solutions while stabilising existing systems under the stress of increased data was also challenging for public health systems in many countries [29]. For example, the MiBa system[1] (a Danish microbiology database providing a national automatically updated database of microbiological test results) in

[1] https://mibaen.ssi.dk/miba

Denmark was described as a 'somewhat fragile system built in haste,' and there were limited people with in-depth knowledge on the complexity of the infrastructure, coding, and data it contained [29].

Many European countries established additional systems and databases to enhance early detection and tracking of COVID-19 [38]. Specific examples of new digital infrastructure that were implemented during the pandemic include Italy's creation of an Integrated Surveillance System with a web platform for data sharing [26], and the formation of the National Reference Centre for Whole Genome Sequencing supported metagenomics-based SARS-CoV-2 surveillance [39]. Italy also developed I-Co-Gen (Italian-COVID19-Genomic) to facilitate data sharing and analysis of SARS-CoV-2 genomic data [40]. In Denmark, the National Electronic Requesting and Reporting System utilised nationally mandated MedCom standards for requisitioning, reporting, and data transfer to MiBa [29]. Some EU/EEA countries such as Denmark and Belgium had digital infrastructure to help track the pandemic in real time, which integrated different sources of data (e.g. healthcare data, national patient and immunisation registries, environmental and wastewater surveillance data). This helped improve their ability to identify clusters and outbreaks, and make evidence-based decisions about their response [16,29,41,42].

EU-level networks and platforms also helped support data sharing and data integration during the pandemic. For example, the European Surveillance System (TESSy) platform helped facilitate data integration, and support was also provided by the European COVID-19 surveillance network (ECOVID-Net), the European Influenza Surveillance Network (EISN), and the European Union SARI surveillance network (E-SARI-Net) [43].

Other ways countries attempted to improve digital infrastructure during the pandemic according to interviewees were through platforms to help with automated data management and analysis, web services for data submission to the national surveillance system, and expansions of e-health systems for closer to real-time reporting. This was echoed in survey responses, where 81% of participants noted that data management and sharing systems were implemented in PHLs to mitigate challenges.

Interviewees also highlighted the importance of interoperability and linkage between different data systems to allow for data sharing during health emergencies, and the utility of a centralised database for all diagnostic testing results. Digital infrastructure is critical to facilitate linkages between data sources and integrated surveillance, and can help streamline processes and improve data accuracy [29]. On an international level, harmonised standards and protocols are also needed to be able to integrate and compare data across sources [44]. Participants in the technical meeting highlighted the effectiveness of data sharing platforms for integrating data from different sources in public health activities, including platforms that facilitate combining laboratory test results with clinical data from healthcare. Several participants stated their intention to maintain these in peace time.

These experiences during the COVID-19 pandemic show that digital infrastructure was key to sharing, storing and analysing data from different sources. In cases where this is lacking across EU/EEA countries, investment in digital infrastructure can help improve preparedness for future health threats.

Capacity varied between EU/EEA countries, which affected the quality and the comprehensiveness of data available to understand the COVID-19 pandemic.

Maintaining a high level of activity over the long term strained resources, especially in smaller countries. Public health laboratories needed substantial financial investments, logistical coordination, equipment and digital and physical infrastructure.

In some areas within individual states, there were also disparities in resourcing, expertise, and health system responses across different regions. For example, uneven levels of expertise and training across laboratories and institutions led to disparities in data quality, security and accessibility, further complicating data sharing initiatives [44]. In countries like Italy and Spain, regional diversity and decentralised health systems resulted in varied local responses, despite national public health guidelines, leading to differing case definitions and testing strategies. For example, in Italy, the rapid spread of the virus in early 2020 was exacerbated by insufficient epidemiological capabilities and the failure to systematically track unusual infection spikes across regions [26]. Countries also differed in the degree to which they collected (and linked) wider data sources such as medical records, epidemiological and demographic information, which made it difficult to identify high-risk groups for COVID-19 and understand health inequalities in the pandemic [45].

Genomic surveillance was important in understanding variants of SARS-CoV-2, but its implementation was challenging in several countries.

To effectively respond to emerging variants during the COVID-19 pandemic, countries needed to rapidly share genomic information and have high sequencing capacity [27]. While detecting a small number of specific mutations can be done quickly in most molecular biology laboratories (e.g. with SNP specific RT-PCR assays), capacity and availability of sequencing technology was often insufficient in understanding variants of concern more fully through whole genome sequencing (beyond known individual variants).

Capacity for genomic surveillance was a significant challenge for many countries during the pandemic, and 91% of survey respondents identified introducing and scaling up genomic surveillance as a key challenge for PHLs.

Interviewees noted that while genomic surveillance was needed to identify emerging variants, many laboratories lacked the necessary infrastructure and resources for large-scale sequencing, particularly at the beginning of the pandemic. In Germany, it was reported that sustaining large-scale genomic surveillance presented significant financial and logistical challenges [46], and in Belgium, the lack of federal funding delayed the development of genomic surveillance systems [47]. In a Spanish region, delays in obtaining whole genome sequencing meant they acted cautiously, assuming the variant was of concern rather than waiting for conclusive confirmation [10]. Disparities between countries in the capacity for conducting genomic surveillance hindered efforts to track the emergence and spread of variants globally, potentially delaying the detection of variants of concern [34]. This highlights the need to develop the capacity to obtain and analyse genomic data quickly [10], and the need to support countries with resource constraints in accessing costly sequencing and related supplies [35].

Data sharing

The COVID-19 pandemic highlighted challenges in accessing and sharing essential data and biological samples, which are crucial for effective disease surveillance and response. This contributed to insufficient and uneven access to data across countries, particularly data and biological samples for genomic surveillance [33]. Interviewees and workshop participants discussed that data sharing between partners was slow and that incompatible IT systems across partners involved in surveillance hindered data sharing.

Regulatory considerations and privacy concerns limited and slowed data sharing during the pandemic.

Data sharing was often difficult due to concerns about data protection and privacy, particularly for genomic and for person-identifiable data. During public health emergencies, PHLs and agencies needed to navigate regulation around sharing clinical samples and data (e.g. General Data Protection Regulation (GDPR) requirements) [14] and ethical governance frameworks [29]. For example, the MiBa system implemented in Denmark encountered challenges due to the stringent requirements of the EU GDPR surrounding person-identifiable data, which hindered comprehensive research on COVID-19 [29].

To better prepare for future health threats and to speed access to data and samples, clear guidance around sharing clinical samples can be helpful. Several participants from the technical meeting highlighted the need to clarify how the GDPR applies to sampling and meta data sharing during a pandemic (and peacetime), depending on how the regulation is interpreted within their country. Participants also raised questions about how the In Vitro Diagnostic Regulation applies to diagnostics used in public health activities during a pandemic. Resolving these issues prior to emergency situations can help prevent them from slowing down data sharing and testing procedures when they matter most. Greater clarification of the legislative and regulatory framework for data and sample sharing would also help identify where institutions and countries interpret them differently, leading to challenges in data and sample sharing during emergency situations.

Along with greater clarity around existing regulations, new regulation may also be needed to facilitate data and sample sharing within countries and across borders. For example, an interviewee reported that in Denmark, a new law was put in place to allow for sharing microorganism sequences during the pandemic.

Structures to support coordination amongst public health laboratories and others involved in public health activities helped facilitate data sharing.

Challenges in coordination also affected data sharing. Interviewees mentioned that the decentralised nature of some public health systems, as seen in the Netherlands and Sweden, hindered the coordination of sample and data transfer, therefore impacting testing capacity between regions. In Portugal, SARS-CoV-2 testing initially occurred at the National Reference Laboratory (NRL) but was later decentralised to include public and private laboratories. However, the lack of unified information systems made communication between different levels challenging [11].

Even when data were shared, there were challenges in data accessibility and interpretation across different types of stakeholders involved in surveillance. Data that were shared across surveillance partners often lacked key information that would be helpful in understanding and interpreting SARS-CoV-2 tests and pathogen-level data (e.g. epidemiological information such as the reason for test request, patient symptoms, exposure data) that can help uncover transmission patterns and understand health inequalities [29].

At an international level, harmonised standards and protocols are needed to be able to integrate and compare data across sources [44]. International platforms can also be drawn on during public health emergencies, for example, pre-existing platforms like the Global Initiative on Sharing All Influenza Data (GISAID), which was broadly used across EU/EEA countries, facilitated sharing information to SARS-CoV-2 variants [40,48]. For future respiratory infectious diseases, it may be possible to draw on existing international collaborations and platforms to facilitate more timely data sharing [26,27].

Several participants in the consultation meeting expressed a desire to maintain and build on the improvements in data sharing made during the pandemic. Specific examples included improved data sharing between PHLs and public health authorities in individual countries, better data transfer between PHLs and regional hospitals, and the

expansion of databases for genomic surveillance that aid in data sharing. Participants suggested that creating venues for sharing knowledge about data management and data sharing pipelines might be helpful, and that open data systems that allow data to be shared with external partners (e.g. universities, private sector actors, healthcare providers) can be especially valuable in emergency situations.

Coordination and collaboration

National and international collaboration was critical in supporting public health laboratories during the COVID-19 pandemic.

Coordination between laboratories and public health institutions, and between stakeholders in different regions and countries are critical components of a robust pandemic response [44] and were key aspects of PHLs' response to COVID-19 across EU/EEA countries [15,26] and internationally [35,44,49]. For example, interviewees and meeting attendees emphasised the importance of collaboration amongst PHLs and public health agencies, government stakeholders, healthcare providers, international partners, academia and private sector companies during the pandemic.

International collaboration was vital for sharing data, expertise and resources. For example, collaborations amongst regional and national microbiology laboratories, health authorities and genomic sequencing platforms were crucial in enabling surveillance during the COVID-19 pandemic [10,16,35] and helped share best practice and knowledge, bridging gaps in particular geographical areas [35,49]. International collaboration was also helpful in building capacity during the COVID-19 pandemic. For example, in the early months of the pandemic, countries that had not yet implemented molecular tests for COVID-19 arranged to ship their samples to specialised laboratories abroad [14], which was noted by technical meeting participants as helpful in filling capacity gaps and processing samples quickly. Financial and logistical support from WHO and other partners also helped countries access essential equipment and expertise, ensuring equitable access to genomic surveillance capabilities [35].

Other examples of international networks and collaborations established during the COVID-19 pandemic include ECDC and WHO European Regional joint laboratory network and surveillance calls, ECDC-initiated SARS-CoV-2 virus characterisation working group, European COVID-19 reference laboratory network and wider surveillance network European COVID-19 surveillance network, and the European Commission's technical working group on COVID-19 diagnostic tests (19,50–52). Initiatives like EpiPulse also encouraged EU/EEA countries to report suspicious signals related to SARS-CoV-2 virus, and the network of National Public Health Institutes (NPHIs) in the EU enabled information exchange through bi-weekly conference calls to compare data and share best practices [38,53]. In addition, WHO convened a working group of experts from 25 countries to help enhance nearer to real-time global surveillance data, while the European Commission Joint Research Centre in partnership with the Health Emergency Preparedness and Response Authority launched a Global Consortium for Wastewater and Environmental Surveillance for Public Health (GLOWACON) [33,54]. The WHO European region also hosted bimonthly 'COVID-19 variants and mutations updates call' for ministries of health to discuss genomic surveillance data, encouraging transparency and collaborative problem-solving.

Within-country networks were also important and specific examples of within-country networks included Spain's RELECOV network [48], Italy's WGSnet-Lazio network [40], and Belgium's national sequencing consortium [47], which were all developed to increase sequencing capacity and facilitate genomic surveillance. In Spain, a coordinated effort between the Epidemiological Surveillance Unit (responsible for contact tracing and public health interventions) and the laboratory teams performing genetic analyses helped ensure that laboratory findings were rapidly communicated to the relevant public health officials, enabling timely implementation of control measures [10]. Germany's IMS-SC2 network, comprising 16 diagnostic laboratories, also enabled a coordinated and standardised approach to sample collection and processing, facilitating the implementation of new techniques across multiple laboratories [46]. Denmark's network of clinical microbiologists, IT experts, and public health officials facilitated the rapid development of algorithms for identifying new COVID-19 cases and integrating data from various sources [29].

Collaboration across different sectors was also important in facilitating public health activities and help with the interpretation of data from different sources and the development of prevention strategies and clinical care [44]. For example, early in the pandemic, Italy used food safety laboratories to increase testing capacity, facilitated by their integration at the national level with the Ministry of Health [26]. Similarly, an interviewee noted that in Lithuania, PHLs worked with veterinary and private laboratories.

Collaboration between PHLs and the private sector was also crucial for coping with high demand in many countries. In some cases, this was achieved by expediting the accreditation process for private laboratories, enabling a strong laboratory network [22]. In Finland, collaboration with the Finnish Medicines Agency (Fimea) facilitated prompt regulatory action, allowing for the use of commercial assays. Public-private partnerships also leveraged resources and expertise, enhancing genomic surveillance capabilities. In Germany, for example, the federal government required insurance companies to pay for tests for symptomatic individuals, prompting private laboratories to rapidly increase testing capacity, potentially reducing the burden on PHLs [26].

Improving collaboration requires clear structures to support coordination, communication and trust.

Although many networks were established during the COVID-19 pandemic, the public health emergency also revealed challenges in coordination and collaboration. These challenges, in part, were due to the absence of a universally agreed global authority to direct and coordinate international collaboration which led to inconsistencies and inefficiencies in communication and coordination between different laboratories and countries [44]. Creating clear lines of communication and establishing defined roles and responsibilities is important in improving how collaborations function, especially during public health emergencies [44]. Mapping can be used to identify relevant partners for PHLs, to help define roles and understand how organisations can work together, and to foster strategic partnerships [35].

Workshop participants highlighted the centrality of trust and open collaboration in supporting good relationships between partners involved in surveillance, including PHLs. Participants expressed that the networks and communication channels established during the pandemic should be preserved and strengthened to improve preparedness, and some mentioned the role of ECDC and other EU institutions in facilitating this. However, some interviewees and workshop participants said that current good relationships may be reliant on individuals, and some reported an effort to move towards a more process-oriented approach as opposed to person-centred approaches.

Reporting requirements are also a way to facilitate coordination during emergencies. While mandatory reporting requirements exist for certain infectious diseases, challenges remain in establishing real-time communication channels and fostering a culture of proactive information sharing, especially during the early stages of a potential pandemic [44]. For example, some have advocated for the widespread adoption of the Incident Command System (ICS) as a framework for managing pandemic response efforts, emphasising its modular nature and ability to facilitate coordinated action among various stakeholders. However, the inconsistent application of ICS principles across different regions and countries can create challenges in harmonising data sharing protocols and coordinating efforts between laboratories and institutions operating under different management structures [44].

An example of an existing EU level coordination mechanism is the Early Warning and Response System (EWRS), a restricted communication platform for alert and risk management of serious cross border threats to health [55]. The EU has also helped promote coordination by defining the pathogens under EU-level surveillance in the Commission Implementing Decision (EU) 2018/945 (56) and creating a reporting protocol for each disease, including COVID-19 [57].

How public health laboratories can move forward from the COVID-19 pandemic

This chapter examines the scientific advances achieved during the COVID-19 pandemic and the lessons learned to improve preparedness for future health threats. We discuss advances in sequencing techniques, bioinformatics infrastructure, and environmental surveillance, along with the need to sustain these developments through funding, workforce training, and strengthened collaboration.

Scientific advances made during the pandemic

Maintaining the significant advances that were made in genomic surveillance, wastewater surveillance and other methods can help improve preparedness in public health laboratories

During the pandemic, the emergence of variants of concern made genetic and genomic surveillance essential for monitoring virus evolution and informing public health responses [10,30,33,34,44,48,58].

Although introducing and scaling up genomic surveillance was identified as a challenge by most survey respondents, genomic and metagenomic surveillance progressed rapidly during the pandemic, both in terms of method development and the scale at which they were used [35,48,49,59,60]. These advances offer an opportunity to improve preparedness for future health threats by integrating them into routine laboratory processes. Since 2020, the capacity for wastewater monitoring has grown [42], and advances have been made in sample processing and assay sensitivity of wastewater systems [59].

Interviewees and technical meeting attendees said sustaining these advances is crucial to improving preparedness for future respiratory threats. They mentioned several key areas that require attention, including ensuring sustainable funding, maintaining enhanced capacity, improving infrastructure, and strengthening collaboration around these types of surveillance.

Maintaining and improving the genomic surveillance capacity requires a skilled workforce to process and analyse data, and interoperable bioinformatics infrastructure to manage the vast array of data relevant to genomic

surveillance [29,34,44]. Sustaining advances in genomic surveillance will also require considering the logistical aspects of integrating genomic surveillance into existing surveillance mechanisms [35].

Although the pandemic led to advances in genomic and environmental surveillance, there are gaps in scientific knowledge, best practice and pipelines for data. Building on advances in genomic and environmental surveillance will require further research, the development of guidelines and policies, quality assurance mechanisms and strengthened collaborations to share data and jointly sequence and analyse samples [33,40,42,48,60].

Improving preparedness requires the right kind of genomic surveillance.

One of the lessons from the COVID-19 pandemic is that both high-throughput screening (e.g. allele-specific PCR, RT-qPCR, spike screening technologies) and whole genome sequencing techniques were important in understanding variants [10,34]. Along with the right mix of genomic surveillance techniques, improving the timeliness of whole genome sequencing more widely can also help improve response to future health threats by providing earlier detection and informing more targeted interventions [10]. Participants in the consultation meeting also underlined the need to disseminate techniques that can be deployed quickly, relatively cheaply and without intensive training in emergency situations, including simpler sequencing techniques. One participant noted the need to invest in high throughput diagnostic capabilities to rapidly scale up testing during surges; and another the need for investment in advanced surveillance systems to identify unusual patterns of disease and emerging pathogens, including expanding genome sequencing capabilities and improving real time data sharing across laboratories.

During the technical meeting, participants from EU/EEA countries and EU institutions also reflected that more research is needed on the types and intensity of surveillance required at different points in a public health emergency. Participants highlighted the importance of wastewater surveillance for rapid reaction to new pathogens and felt more evidence was needed to establish best practice. More analysis is needed to determine the appropriate volume of sequencing at different stages of a pandemic and the role of PCR testing compared to more rapid tests. In retrospect, many participants felt that too much sequencing and PCR testing occurred during the COVID-19 pandemic and that the resources should be better prioritised next time.

Summary of lessons learned from the COVID-19 pandemic

Timely and adaptive testing and surveillance is important to mount an effective response to public health threats

The COVID-19 pandemic demonstrated that speed and efficiency is key during public health emergencies, both in terms of developing and implementing new testing methods in laboratories [15] and ensuring timely insights from these methods [33]. For example, for genomic surveillance, it is important that methods provide timely insights to respond to health threats [58,60,61], particularly when identifying new mutations or assessing potential variants of concern. Efforts to improve rapid sequencing and analysis may include using artificial intelligence to analyse genetic and epidemiological data (e.g. to detect novel pathogens and outbreaks, and to investigate the significance of different mutations) [33], and drawing on capacity within laboratory, academic and cross-sector networks to rapidly sequence and analyse samples [40].

Adaptability is also a key aspect for improving PHLs' ability to respond to demands [10], for example, so that existing infrastructure for respiratory infectious diseases can be used for new health threats [27]. It is also important to be able to select methods and techniques that align with surveillance objectives (e.g. early detection) and with the characteristics of variants in circulation [53].

Interviewees provided an interesting perspective on speed and agility, and how the organisation of public health systems express these key attributes during pandemics. For example, some interviewees reflected that countries with centralised systems may be better able to implement new measures (e.g. mass testing and genomic surveillance) than those with decentralised structures. However, regardless of structure, the need for flexibility and agility was clear: laboratories needed to be able to adapt protocols and optimise techniques based on new information, and then quickly implement changes.

Combining diverse data sources can enhance outbreak identification and response

During a pandemic, multiple data sources are relevant to decision making. Some EU/EEA countries had digital infrastructure to help track the pandemic in real time, which integrated different sources of data (e.g. healthcare data, national patient and immunisation registries, environmental and wastewater surveillance data). This helped improve their ability to identify clusters and outbreaks, and make evidence-based decisions about their response [16,29,41,42]. Collecting additional data alongside COVID-19 test results, such as symptoms and reason for testing, also helped countries interpret results [29].

During future health emergencies related to respiratory infectious diseases, existing infrastructure can be used to share data, as was done during the COVID-19 pandemic (e.g. the European Surveillance System (TESSy), the Global Initiative on Sharing All Influenza Data (GISAID). Doing this would also build data resources that can be used to conduct research on how respiratory pathogens spread, beyond what is possible with datasets on single pathogens [27].

Preparedness is important in 'peace time' to be able to respond to future health threats

During the pandemic, public health systems in EU/EEA countries gained experience in responding to a novel public health threat, conducting activities in the context of an emergency, and collaborating and coordinating across different levels. However, over time, this immediate and applied experience may fade. Interviewees and workshop participants reported that one of the most prominent lessons learned from the pandemic was the critical importance of preparedness.

Participants from EU/EEA countries and EU institutions indicated that during 'peace time', preparedness and response plans should be developed to define how PHLs and other actors within public health should respond in future public health emergencies. These plans could help reduce the need to be reactive and build relationships during emergency situations in the future, when mistakes can occur and when decision-making may be less effective due to high pressure. Participants also noted that existing preparedness plans may need to be revisited to take account of the lessons learned during the pandemic, rehearsed during 'peace time' to maintain the capacity to respond during emergencies, and refined using simulation exercises that test how systems will respond during future respiratory health threats. While this can happen at a national level, participants from EU institutions discussed the utility of simulation exercises focused on pandemic preparedness across countries.

For many, the COVID-19 pandemic demonstrated the importance of keeping preparedness on the political agenda. This was a central theme in discussions at the technical meeting, and was described as a pre-requisite for implementing many of the improvements needed to increase preparedness, particularly as the immediate threat of the COVID-19 pandemic has faded. Many participants mentioned that improving preparedness within PHLs will require sustained funding for public health activities and PHLs during 'peace time' in order to be prepared for potential future emergencies, including through earmarking money specifically for preparedness and surveillance within PHLs.

Preparing for novel pathogens is critical to improving overall preparedness.

Many of the lessons from the COVID-19 pandemic are particularly relevant to improving preparedness for novel pathogens (as SARS-CoV-2 was a novel pathogen). When asked to select the three most helpful solutions for novel pathogens, half of the respondents to our survey (n=16) selected the introduction and expansion of genomic surveillance. The next most frequently selected options were additional funding for PHLs, international laboratory networks and collaborations, and new laboratory procedures and techniques, which were each chosen by 38% of participants.

Many of these approaches are discussed above, however, genomic surveillance and metagenomic approaches are particularly important for understanding novel pathogens and identifying genetic characteristics and mutations. Metagenomics can be used to identify potential threats and assess the risk of different mutations and the risk that pathogens in animals and the environment pose to human health [33]. In the aftermath of the COVID-19 pandemic, these types of approaches can help avoid the trap of only preparing for viruses similar to SARS-CoV-2 [59]. Metagenomic surveillance, advanced molecular detection techniques and environmental surveillance also expand the opportunity to conduct pathogen-agnostic surveillance programmes, improve preparedness for future pandemics and novel pathogens by broadening the range of threats that can be detected, and enhance the ability to look beyond specific pathogens of concern [35,44].

Having a skilled workforce and international collaboration is particularly important to detect novel pathogens. For example, it is important to train staff with the most up-to-date knowledge to enable them to identify unusual or unexpected findings, and to have robust mechanisms for reporting to public health agencies [44]. During the COVID-19 pandemic, collaboration between academia, private sector stakeholders and PHLs helped improve access to information and skills to facilitate rapid response. For example, private sector organisations provided public health testing services, diagnostic tests and medical countermeasures in EU/EEA countries during the pandemic, and provided laboratory infrastructure to support public health responses [26]. This type of cross-sectoral collaboration and communication can help build technologies and capacity to respond to future health threats caused by respiratory diseases.

Many novel pathogens with pandemic potential are zoonotic. Improving the ability to conduct One Health surveillance across human health, animal health, and agriculture is critical to improve preparedness for future health threats [59]. To build these capabilities, data sharing challenges that inhibit cross-sector information sharing need to be addressed and communication and coordination mechanisms need to be improved. Additionally, shared ways of working are needed to bolster coordination across stakeholders in different sectors during public health emergencies.

Improving preparedness outside of public health laboratories to improve public health outcomes.

Activities within diagnostic laboratories, and mobile laboratories facilitated faster surveillance during the COVID-19 pandemic [11,28,29]. For example, mobile testing in Denmark provided testing services in remote areas, and supported local outbreak responses [29]. Rapid diagnostics and effective contract tracing systems will likely be important in responding to future public health threats [10]. While many of these activities fall outside the scope of this study, there are several lessons that are relevant to preparedness initiatives more broadly.

Improving the ability to rapidly implement new testing methods can enable clinical and diagnostic laboratories to provide sufficient high-quality data to support public health activities during pandemics. In addition, providing practical support to clinical and mobile laboratories to ensure they have supplies (e.g. PPE), staff and training can help improve preparedness [15,28,62], and was a key part of many PHLs' role during the pandemic. To support mass testing during future public health emergencies, cost-effective methods and evidence-based asymptomatic testing strategies are needed, alongside resources for these testing programmes [63]. New working patterns (e.g. to facilitate isolation) and training for staff, along with strengthened collaboration to share capacity and best practice, can also be helpful to improve the data coming from clinical laboratories during future health threats [11,15,28,29,64].

Interventions aimed at strengthening diagnostic laboratories include improving supply chain management, enhancing emergency planning, standardising operating procedures and improving data reporting systems [15,28–30,44,63,64]. Addressing accreditation and regulatory hurdles for clinical laboratories accessing samples from multiple sources (e.g. veterinary, research samples) can also help improve capacity [26].

New techniques and up-skilling staff in these methods may help improve surveillance for future respiratory diseases. For example, during the COVID-19 pandemic, molecular diagnostic capabilities (e.g. PCR) in hospital laboratories were particularly important, which required up-skilling staff and introducing new ways of working [28]. Interviewees reported that although some rapid and hospital-based methods such as antigen tests were less sensitive than more complex methods used in PHLs, these less sensitive tests were important in reducing the burden of PCR testing in PHLs. In countries that implemented self-sampling systems, this also reduced the need for healthcare personnel and PPE, although there is a need for training in self-sampling (and understanding the effect of poor sampling practices) if this is implemented in future pandemics.

The role of EU institutions in public health laboratory preparedness

This chapter examines the role of EU institutions in enhancing the capacity, coordination, and preparedness of PHLs to address public health emergencies. Drawing on insights from technical meetings and stakeholder discussions, the chapter explores challenges that hinder the effectiveness of PHLs including ensuring continuity of funding and resources after the expiration of EU programmes and grants, addressing staffing and capacity gaps during non-crisis periods, and clarifying the roles and remits of EU institutions.

Guidance and regulatory frameworks

In the previous chapters we discussed the importance of clear and flexible guidance at different points during the pandemic. The guidance that EU institutions such as ECDC issued during the pandemic were vital in guiding country-level action and disseminating best practice during the pandemic. During the technical meeting, participants raised concerns about some gaps in guidance and standardised protocols, including genomic surveillance, maintaining expertise and capacity in 'peace time', clarifying the role of different data sources in surveillance, and distinguishing the roles and responsibilities of different types of laboratories in public health emergencies. Filling these gaps can help improve surveillance strategies, laboratory processes and preparedness. Some participants also highlighted the EU's role in conducting external quality assessments of laboratory activity and in conducting risk assessments to understand upcoming threats, which was described as valuable during the pandemic. Some examples of external quality assessments and risk assessments were also identified in the literature [18,65,66].

Several participants in the technical meeting also underlined the need to clarify how GDPR should apply to data and sample sharing in emergency situations, with some highlighting the role of EU institutions in providing clarity. Many attendees from EU/EEA countries and EU institutions also said there are continued challenges around the EU's regulation on In Vitro Diagnostic Regulation medical devices [67]. Despite provisions designed to allow flexibility in emergencies, participants reported that this regulation still limits the ability to develop and validate tests during public health emergencies involving novel pathogens.

Funding

Participants from EU institutions underlined the importance of EU-level investment in research during the technical meeting, particularly in relation to novel pathogens, rapid detection and characterisation of viruses (e.g. central sequencing services), and the rapid development of diagnostics, antivirals and vaccines. For example, during the pandemic, approximately 26 million Euros were used to sequence almost 240 000 SARS-CoV-2 genomes from EU and Western Balkan countries by EU Commission and ECDC funding [68]. Funding research and other initiatives in these areas could speed up the development of medical countermeasures and laboratory techniques in the event of a future pandemic.

Participants in the study highlighted the value of EU programmes and grants in improving laboratory infrastructure and meeting demands in PHLs during the pandemic. However, participants reported difficulties and uncertainty around a lack of sustained funding and underlined the importance of clarity on whether further EU support would be forthcoming to enable capacity to be maintained. For example, some participants noted that programme funding from EU institutions was invaluable during the pandemic but left a funding void once those programmes came to an end. One participant mentioned that this created difficulties during this year's flu season (2024/25), as the PHL they were responsible for was understaffed.

Collaboration and coordination

Participants highlighted the role of ECDC and other EU institutions in communicating with EU/EEA countries and PHLs, and in coordinating the different actors involved in public health activities. For example, participants said that they saw a role for the EU in facilitating coordination between countries in future pandemics, including by supporting emergency preparedness and continuity planning; stronger-EU wide laboratory networks; sharing of best practices; standardising protocols where needed; and coordinating stockpiling of diagnostic kits, reagents and reference materials for priority pathogens. Participants also underlined the importance of communication from EU bodies, both in 'peace time' (to encourage countries to prioritise and fund preparedness) and during public health emergencies.

Planning for future public health emergencies

Technical meeting attendees from EU institutions made a number of suggestions for next steps to improve how future public health emergencies are handled at the EU level. They identified the key role of EU institutions in helping countries establish and rehearse preparedness and escalation plans to enable a more streamlined and effective response to future public health emergencies.

EU-level stakeholders also emphasised the importance of clarity around the different EU institutions' remits, which was not entirely clear in the pandemic and was perceived to reduce trust in the support being provided at the EU level. Representatives of EU institutions reported that a mapping exercise to clarify this would be helpful in the future.

Summary and discussion

Public health laboratory experiences during the COVID-19 pandemic

PHLs play an important role in gathering information about respiratory infectious diseases, how they behave and mutate, and how they spread across populations. PHLs in EU/EEA countries faced intense pressure during the COVID-19 pandemic in delivering vast sequencing and mass testing campaigns, in quality assurance, and in supporting hospital and diagnostic laboratories. Along with high demands for laboratory services and the capacity pressures that came from surges in demand, PHLs faced challenges due to pressures around communication and the politicisation of the COVID-19 pandemic more widely.

During the pandemic, PHLs faced challenges related to resource and workforce constraints, infrastructure and digital infrastructure gaps, and supply chain and procurement issues. Conducting genomic surveillance, which required new capacities and skills, was particularly challenging, as was managing, sharing and analysing the enormous quantities of data that this surveillance produced. However, as it was key in detecting, understanding and responding to SARS-CoV-2 variants, genomic surveillance was also identified as a way that PHLs helped resolve challenges in the pandemic. Data sharing, collaboration and coordination was a significant challenge during the pandemic, which affected the timeliness, efficiency and comprehensiveness of surveillance. In addition, the lack of coordination at the national and European levels contributed to challenges in linking data from different sources and conducting integrated surveillance.

To help address workforce challenges, PHLs hired new staff, implemented new ways of working, and trained staff in new laboratory techniques. Guidelines and standard operating procedures helped spread best practice and supported better quality data. To help address capacity constraints, PHLs also drew on capacities in other laboratories and sectors, developed new laboratory networks, procured supplies from new sources or in new ways, and developed in-house assays. Finally, digital infrastructure was essential to support genomic surveillance and data sharing.

Gaps in preparedness

Supporting PHLs during the COVID-19 pandemic was costly, highlighting the need for analysis to identify cost effective strategies for improving preparedness. For example, evidence is needed on 'right-sizing' surveillance, best practice in particular techniques, and how to best integrate wastewater [69] and pathogen agnostic approaches into surveillance. PHLs in EU/EEA countries require support in preparing for future respiratory infectious diseases, including to maintain advances made during the pandemic, preparedness planning, having systems in place for the rapid introduction of new tests and identifying how and when to scale up and scale down capacity to meet demands. Resources, guidelines, networks to help share best practice, and evidence from research studies investigating the most effective surveillance methods for different time points in pandemic can help fill these gaps.

PHLs in EU/EEA countries also require support in addressing issues in coordination and data sharing. Many stakeholders report a lack of clarity in how regulations apply to sharing data and biological material, and technical and logistical challenges in sharing data, linking data between sources, and obtaining good quality meta-data. There is also a gap in coordination amongst different stakeholders involved in PHL activities across countries, and a lack of clear roles and boundaries between EU institutions responsible for responding to public health emergencies, as reported by participants from ECDC and the Health Emergency Preparedness and Response Authority. Although a recent study by the Authority mapped structures with relevant mandates, tasks and functions, this study did not explore the precise divisions of responsibilities and objectives across different EU institutions in relation to pandemic response and preparedness in PHLs [70].

There is an opportunity to learn from the experience of the COVID-19 pandemic to help improve the preparedness of PHLs for future health threats. For example, during the pandemic we learned that speed and agility were important in supporting a successful PHL and wider public health response to SARS-CoV-2. In future public health emergencies, speed, accuracy and quantity of tests will need to be balanced. Information about the types of PHL activity that are most effective in informing decision making at different points in pandemics can help support this. During the pandemic, advances were also made in genomic and wastewater surveillance. Maintaining and enhancing this capacity, building and consolidating knowledge, and spreading best practice in these areas can help improve preparedness for future threats, particularly novel pathogens. Enhancing the capacity to conduct integrated One Health surveillance and pathogen agnostic surveillance which can also help detect threats early.

Options for actions

This study collected evidence on PHL experiences during the COVID-19 pandemic, highlighting challenges, solutions, and lessons learned. The results of this study are informative in highlighting gaps in preparedness and understanding what would be needed to improve PHL preparedness at an EU-level. Participants from PHLs in EU/EEA countries identified EU-level support that would improve preparedness for future respiratory infectious diseases:

- **Maintaining and, where needed, increasing the amount of funding provided to support long-term preparedness** in PHLs through EU funding mechanisms such EU4Health, rescEU and HERAInvest, along with funding provided directly to countries. Along with supporting general preparedness of public health systems, some of this funding should be targeted towards addressing capacity gaps, especially in under-resourced settings, and supporting physical and digital infrastructure.
- **Funding, conducting and collating evidence around best practice related to PHL activities,** including by conducting or commissioning high-quality evidence reviews and expert consultations, and identifying specific evidence gaps in responding to public health emergencies. For example, research is needed to fill the gaps in understanding the needs of decision makers at different stages of pandemics in order to make the best use of available resources**.** This should include evidence to inform: virus characterisation; 'right sizing' surveillance practices; best practice and standardised methods for wastewater and metagenomic surveillance; harmonisation and integration of data; scale up and scale down of PHL involvement in different activities during public health emergencies and during peace time; and communication strategies that PHLs should adopt in future pandemics (where, when and how to communicate with policy makers and the public).
- **Implementing EU-level actions to address supply chain issues** that affect PHLs, including stockpiling of diagnostic kits, reagents and references materials for priority pathogens and Joint Procurement Frameworks amongst EU/EEA countries during emergencies to increase supply and reduce competition between countries.
- **Supporting PHLs in countries to learn from the COVID-19 pandemic and maintain capacities** related to virus characterisation, genomic surveillance, and wastewater surveillance. This support should include efforts to recruit and retain skilled staff, including staff that were trained during the pandemic.
- **Conducting EU-wide preparedness exercises to support flexibility and agility,** and to rehearse plans for when public health emergencies occur. These exercises can help reduce uncertainties around how to respond, anticipate likely challenges in coordination mechanisms, and reduce the degree to which PHLs and other stakeholders involved in public health activities feel they have to react, rather than respond, to emergencies.
- **Clarifying the role that different EU-level actors play in supporting PHL preparedness** in countries, which can help reduce duplication of work, improve institutional coordination, and identify sticking points that may occur during public health emergencies. In particular, technical meeting participants from EU institutions indicated it would be helpful to clarify roles and responsibilities around preparedness amongst the different EU institutions through a mapping exercise and consultation.
- **Strengthening networks and collaboration amongst PHLs, other laboratories, and other stakeholders** to support better coordination and sharing of capacity, data, samples and best practices – this should include measures to map the translation of GDPR and other relevant EU-regulation in countries and to identify inconsistencies and gaps between different countries in how data is collected, recorded and shared. This can be done during peace time to enable preparedness for future pandemics, including by supporting networks that focus on detecting and testing emerging and zoonotic pathogens.

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Annex 1. Methodological annex

Literature search

PubMed and Scopus were used to search the academic literature on this topic, focusing on literature that has been published since and including 2020 given the scope of the study and the timeline of the COVID-19 pandemic. Below (Box 1), we provide the search string for this REA, which was run on the 06/09/2024 (Box 1).

Box 1. Search string for academic literature

(laborator*[Title] OR labs[Title] OR "lab-based"[Title] OR surveill*[Title] OR monitor*[Title])

AND

(laborator*[Title/Abstract] OR labs[Title/Abstract] OR "lab-based"[Title/Abstract])

AND

(Covid*[Title/Abstract] OR "SARS-CoV-2"[Title/Abstract] OR "SARS-2-CoV" [Title/Abstract] OR "novel coronavirus*"[Title/Abstract] OR pandemic*[Title/Abstract])

AND

(change*[Title/Abstract] OR challenge*[Title/Abstract] OR issue*[Title/Abstract] OR problem*[Title/Abstract] OR lesson*[Title/Abstract] OR solutions[Title/Abstract] OR impact*[Title/Abstract] OR implication*[Title/Abstract] OR advance*[Title/Abstract] OR "Disease X"[Title/Abstract] OR improvement*[Title/Abstract] OR enhance*[Title/Abstract] OR future[Title/Abstract] OR preparedness[Title/Abstract] OR readiness[Title/Abstract] OR innovat*[Title/Abstract] OR strateg*[Title/Abstract] OR technol*[Title/Abstract] OR resilien*[Title/Abstract])

AND

("public health"[Title/Abstract] OR surveill*[Title/Abstract] OR monitor*[Title/Abstract] OR detect*[Title/Abstract] OR ((national OR reference) N5 laborator*[Title/Abstract]))

Filters: from 2020 – 2024

Below (Box 2), we provide the search strategy that was used to identify grey literature for this study. The search was run on the search engine Google, on the 4/10/2024.

Box 2. Grey literature search

(laboratory OR labs OR lab-based)

AND

(Covid OR pandemic OR "SARS-CoV-2" OR "SARS-2-CoV")

AND

(challenges OR lessons OR advancements OR impacts OR improvements OR preparedness OR readiness OR innovations OR technology OR resilience)

AND

("public health" OR "national")

[AND

("European Union" OR "EU" OR Europe)

Along with this grey literature search, we also conducted targeted searches to identify other relevant literature. To do this, we reviewed websites of key PHL networks and public health authorities (see Box 3) to identify relevant material.

Box 3. Key websites reviewed

ECDC Disease and Laboratory Networks - Respiratory tract infections (each website):
https://www.ecdc.europa.eu/en/about-ecdc/partners-and-networks/disease-and-laboratory-networks

ECDC Infectious disease topics – COVID-19, Seasonal influenza, RSV:
https://www.ecdc.europa.eu/en/covid-19
https://www.ecdc.europa.eu/en/seasonal-influenza
https://www.ecdc.europa.eu/en/respiratory-syncytial-virus-rsv

ECDC Lessons from the COVID-19 pandemic report:
https://www.ecdc.europa.eu/en/publications-data/lessons-covid-19-pandemic-may-2023

European Commission – Laboratory networking:
https://health.ec.europa.eu/other-pages/basic-page/laboratory-networking_en

WHO – Laboratory networks, WHO CoViNet:
https://www.who.int/teams/regulation-prequalification/regulation-and-safety/laboratory-networks-and-services
https://www.who.int/groups/who-coronavirus-network

Association of Public Health Laboratories (APHL):
http://www.aphl.org

DURABLE Research Network against Epidemics:
https://durableproject.org/

Health Emergency Preparedness and Response (HERA):
https://health.ec.europa.eu/health-emergency-preparedness-and-response-hera_en

In total, this search strategy identified 1178 academic articles. Five texts were included from the grey literature search.

Screening

Academic and grey literature articles were screened against inclusion and exclusion criteria, provided below in Table 2. Following a pilot exercise where four reviewers screened the same 20 articles and compared results to reach consensus on what articles to include, articles were screened using title and abstracts by a single reviewer for each article. Where the reviewer was unsure of whether an article should be included based on the criteria listed below, another reviewer screened the article. Where two reviewers were not able to agree on a decision, a senior researcher reviewed the article and made a decision.

Table 2. Inclusion and exclusion criteria

	Include	Exclude
Topic	New techniques, technologies and practices that were implemented or scaled up in labs during the COVID-19 pandemic in response to challenges, including factors such as ways of working, staffing models and other "soft" changes. Lessons from the COVID-19 pandemic for PHL preparedness Sustaining advances made during the COVID-19 pandemic in PHLs	Existing techniques, technologies and practices in labs that were standard prior to pandemic Lessons from the COVID-19 pandemic or sustaining advances regarding public health in general (not related to PHLs)
Setting	PHLs Clinical labs or non-public health labs with clear connection to public health or surveillance	Clinical labs or non-public health labs with no clear link to public health or surveillance
Country	EU/EEA countries Unclear geographic focus, or articles that are not about laboratories in particular locations	Any other country
Study design and publication type	Reviews (including both systematic and narrative reviews) Primary studies Perspectives and opinion pieces from informed sources Government publications from EU/EEA countries Pre-prints	Abstracts Marketing material Clinical practice guidelines or standard operating procedures Clinical trials Conference proceedings Case studies
Language	English language publications (academic literature) EU/EEA languages (grey literature)	Articles in other languages
Accessibility	Full-text articles	Articles where full text is not available or is only available behind paywalls outside of RAND's and ECDC's subscriptions

Prioritisation

The number of articles that met the inclusion criteria was too large to practicably review them within the scope of this study. To identify the most relevant articles and make the best use of resources, we developed prioritisation criteria prior to implementation (Annex 6).

In total, 43 articles were prioritised for extraction and inclusion in the mapping study. A PRISMA diagram is provided in Annex 2.

Extraction

Articles were then extracted using a framework designed by the research team based on the research questions for this study (see Table 3). The template was designed to capture: information about each article, evidence against each research question, and reviewer reflections regarding the quality of the article. A systematic evaluation of the strength of the evidence within each article was not conducted as a part of this REA, although the key limitations of each article were assessed by reviewers and noted in the extraction template in an informal quality assessment.

Table 3. Extraction template

Basic information	Article type
	Brief description
	Geographic scope
Challenges	Gaps in scientific knowledge about COVID-19
	Capabilities, knowledge and skills within labs
	Lab capacity and demand
	Supply chains and materials
	Access to data and samples
	Coordination and data sharing/standardisation
	Other
Solutions and adaptations	Supply chains and resources
	Physical infrastructure
	Staffing and ways of working
	Lab techniques and procedures
	Protocols and workflow
	Technology and digital infrastructure
	Collaboration
	Other
Impacts and implications	Positive
	Negative
	Neutral/other
Sustaining improvements	Lessons
	What is needed to sustain advances?
Other	Potential sources of bias
	Article quality
	Potential interviewees
	Researcher notes

Interviews

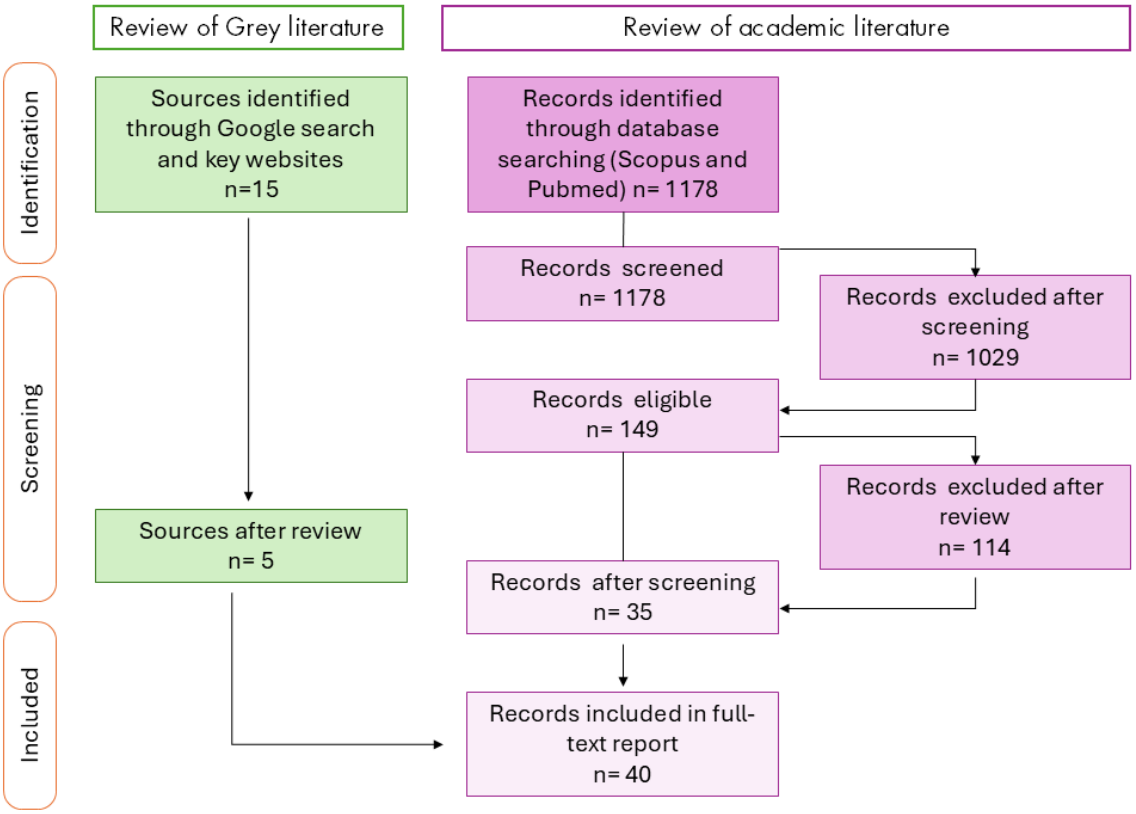
Fourteen interviews were semi-structured (see Annex 3 for protocol) and lasted approximately one hour via Microsoft Teams. Detailed notes were taken during the interview, and interviews were recorded to assist with notetaking with consent from interviewees.

Survey

The survey consisted primarily of closed questions around challenges faced, how laboratories overcame these challenges and views about improving resilience for future respiratory pandemics (see Annex 3 for protocol). There were also two free text questions to gather more in-depth information about PHLs during the COVID-19 pandemic. The survey was designed around the research questions and the results of the desk research and was piloted internally prior to deployment to ensure that questions were clear, easy to understand and unambiguous.

The survey was designed to take approximately 20 minutes to complete and was implemented via an online platform (Smart Survey).

Annex 2. PRISMA diagram



Annex 3. Interview protocol

Background

Thank you for agreeing to take part in this interview. This study has been commissioned and funded by the European Centre for Disease Prevention and Control (ECDC). It will look at challenges that public health labs faced during the COVID-19 pandemic, how these were addressed and the impacts of these solutions. Additionally, it will also look at what is needed to sustain advances made during the pandemic. The goal of this study is to understand how to learn from and sustain advances made during the COVID-19 pandemic to improve preparedness of public health laboratories.

Introduction

This study is focused on public health laboratories, and lessons applicable in EU/EEA Member States. Point of Care Tests and clinical laboratories with no clear link to public health activities are not in scope. For example, we would be interested in surveillance systems, processes or systems between clinical labs and public health labs, but we would be less interested in actual diagnostic tests and we are not interested in clinical care in this study.

Consent

Your participation in this interview is voluntary and you can change your mind about participation at any time. The information that you provide will be treated in confidence by the project team, and results will be reported anonymously, meaning that you will not be named in any reports from this work.

This interview should last around 60 minutes.

We would like to audio record the discussion for analysis purposes, which will be used to help us accurately collect findings for the research. The recordings will be securely stored and retained by us and destroyed after the end of the evaluation.

Are you happy for us to proceed with the recording?

1. **Can you briefly describe your current role and background?**
    a. What is your role in the public health laboratory and experience with pandemic preparedness?
    b. What was your role during the COVID-19 pandemic?

2. Can you briefly explain the **structure of the public health laboratory system** in your country?
    a. [Interviewer note: Please ask the respondent to specify whether they are talking about a specific lab in their response, or if they are referring to experiences across public health labs in general (at a national level).]

Challenges and solutions

3. What were the **main challenges** faced by public health laboratories in [country name] during the COVID-19 pandemic?
    - *Prompt: capacity, turn-around time, supply chains and equipment, access to samples, sharing data, staffing and skills, surveillance methods, technological and scientific challenges, coordination*
    a. Were any of these challenges **specific** to [country name]? If so, why?
    b. Did any of these challenges change over the course of the pandemic?
4. **How** did public health laboratories in [country name] **respond** to the challenges faced by public health laboratories during the COVID-19 pandemic?
    - *Prompt: Technology, scientific techniques, specific laboratory protocols, staffing models, collaborations and networks, infrastructure, data systems, training*
5. In your view what were the **most innovative and novel solutions** that were implemented in your country in public health labs to respond to COVID-19?
    a. Did your country implement anything around new automation solutions or legal frameworks?
    b. What were the key barriers and enablers to the effective implementation and procurement of these novel solutions into the public health laboratories workflows?
6. To what extent were challenges solved in public health labs addressed in a **timely manner** in your country?

   a. What were the challenges in addressing issues in public health laboratories in a timely manner in public health labs during the pandemic?
   b. What helped address issues in a timely manner in public health labs?
7. In your view, how **effective** were any changes implemented during the COVID-19 pandemic in public health labs?
8. Have there been any positive, negative or neutral impacts from adaptations and changes implemented during the COVID-19 pandemic?
9. In your view, what are some adaptations or changes that were implemented during the COVID-19 pandemic that **worked particularly well, or have the potential to work well in next respiratory pandemic**?
   a. Similarly, is there a change that has **not worked well**? If so, please describe.
10. In retrospect, are there any **other solutions** you think would have been helpful in addressing challenges faced by public health labs during COVID-19, which were not implemented? *Prompt: Why were they not implemented?*

Learning from COVID-19

11. What changes implemented during the COVID-19 pandemic within public health laboratories do you think should be sustained in the long-term to improve preparedness for future respiratory threats?
   a. What changes have been incorporated into long-term preparedness in your country's public health labs?
12. In your view, what are the **most important lessons and advancements** from the COVID-19 pandemic that can help improve preparedness for future pandemics?
   a. How can this advancement be applied to future respiratory pandemics?
13. What advancements would be particularly helpful for public health laboratories in **identifying t**hreats related to novel respiratory pathogens in the future?
   a. What advancements would be especially beneficial for public health laboratories in r**esponding to** threats posed by novel respiratory pathogens, particularly when their characteristics are not yet fully understood?
   b. Are there any advancements that you think would be particularly helpful in **identifying and responding to** a new respiratory pathogen pandemic with different characteristics to COVID-19? Prompt: such as pathogens that evolve faster, are more transmissible or are more harmful (cause greater morbidity and mortality) than COVID-19 ?

Sustaining advances

14. What **type of support and resources** would be required to sustain advancements made during the COVID-19 pandemic in public health lab resilience and preparedness?
   - *Prompt based on advancements mentioned earlier in interview*
15. What long-term strategies do you think can help improve pandemic preparedness in public health labs?
   a. Are there any strategies that you think would be particularly helpful in [country]? If so, please explain why.

Improving preparedness

16. Based on your experience, what do you see as the **most significant gaps in public health laboratories in** [country name] in terms of preparedness for future respiratory infectious diseases and pandemics?
17. What would [country] need to improve the preparedness of public health labs for future pandemics?
   a. *Prompt if answer is funding:*
      i. To what extent was the use of available funding efficient? To what extent was it well allocated?
      ii. Are there non-funding mechanisms that might also support [country] in improving preparedness in labs?
18. What types of support functions were useful at the EU level during the COVID-19 pandemic, and what EU-level actions would enhance national laboratory preparedness in the future?

Conclusion

19. Is there anything we may have missed during our conversation that you feel is important for the purpose of this study?

Annex 4. Survey protocol

Questions	Answer option	List
What is your current role?	List, and Other (Free text)	National Focal Point for Respiratory Viral diseases, National Focal Point for Microbiology, Operational Contact Point COVID-19 Microbiology, Operational Contact Point Influenza Microbiology, Operational Contact Point Epidemiology Other
In what country is your current role?	List	List of EU/EEA countries
Which of the following **challenges** were experienced by public health laboratories in your country during the Covid-19 pandemic?	List of options – Select all that apply + Other (free text limited characters)	Gaps in scientific knowledge about the SARS-CoV-2 virus (e.g. mutations, transmissibility, biohazard level) Gaps in scientific knowledge about the best laboratory techniques, protocols and methods to use Gaps in technical skills and knowledge amongst public health laboratory staff Challenges introducing and scaling up genomic surveillance High demand for laboratory services Staffing capacity constraints Constraints in physical spaces Challenges with supply chains and equipment (e.g. PPE, reagents) Mixed or unknown quality of lab procedures and equipment Limited access to clinical samples Challenges sharing data (e.g. privacy concerns, logistical issues) Challenges with data and information management Lack of harmonisation or standardisation in data Challenges coordinating between laboratories and institutions Negative impact on testing, surveillance and reporting for other infectious diseases
To what extent did each of the **challenges you selected negatively affect the ability of public health laboratories** to function at normal capacity and to fulfil public health duties such as surveillance and reporting?	List of options (**from those selected**)– 1 – Not at all 2 – Slightly 3 – Moderately 4 – To a large extent 5 – To a very large extent – It caused critical issues in public health labs.	
Which of the following were put in place within public health laboratories in your country to address challenges during the COVID-19 pandemic?	List of options – Select all that apply + Other (free text limited characters)	Additional staff Different staffing models Introduction or expansion of environmental and wastewater surveillance Introduction or expansion of genomic surveillance New laboratory procedures and scientific techniques Technologies and innovations (including AI, automation, robotics) Training or up-skilling of staff Lab networks and collaborations (within country) Lab networks and collaborations (international) Public/private partnerships Quality assurance measures Data management systems Other digital infrastructure Non-digital infrastructure Guidelines and regulation to support data sharing Additional funding to public health labs
To what extent were **each of the solutions that were implemented in your country effective** at resolving challenges faced during the COVID-19 pandemic?	List of options (**from those selected**)– 1 – Not at all 2 – Slightly 3 – Moderately 4 – To a large extent 5 – To a very large extent	
What changes implemented during the pandemic within public health laboratories do you think should be **sustained in the long-term to improve preparedness for fut**ure respiratory threats?	List of options – Select all that apply **(Limit to 5)** + Other (free text limited characters)	
Which **three solutions** do you think would be most helpful in **improving public health laboratory preparedness for novel respiratory pathogens**?	List of options – Select all that apply (Limit to 3) + Other (free text limited characters)	Increased prioritisation in political agenda Pooled procurement or supply of laboratory equipment and materials Other supply chain resilience strategies Guidelines and protocols for laboratory procedures Regulations and guidelines to help with data sharing and data harmonisation/standardisation Tools and guidelines for wastewater and environmental surveillance Tools and guidelines for genomic surveillance Training materials for laboratory staff Mechanisms to facilitate international collaboration and coordination Distribution of tasks among countries Digital infrastructure (e.g. for data sharing) Non-digital infrastructural support (buildings, transport, etc.) Assistance with assessing scenarios and planning for public health emergencies Additional funding
To what extent do you think the following items would be helpful in sustaining advances made during the COVID-19 pandemic?	List of options **(Up to 5)**– 1 – Not at all 2 – Slightly 3 – Moderately 4 – To a large extent 5 – To a very large extent Other (limited characters)	

Questions	Answer option	List
What do you think is the single most important lesson learned from the COVID-19 pandemic that can improve preparedness for future respiratory infectious diseases in public health laboratories?	Free text	
If you have any further comments that have not been captured appropriately in the survey above, please list these here.	Free Text	

Annex 5. Coding framework

Category	Details
Source	
Priority	
Researcher allocation	
Author	
Year	
Title	
Category	
Description	
Brief description of article	
Geography	
1. Challenges	
1.1 Gaps in scientific knowledge about Covid-19	Gaps in knowledge or research about the virus, its transmission, treatment, long-term effects, etc.
1.2 Capabilities, knowledge and skills within labs	Gaps, challenges around the expertise, technical skills, and competencies of laboratory personnel, technologies and methodologies, which enable precise, efficient testing, research, and analysis, etc.
1.3 Lab capacity and demand	Challenges that affect the PHL's ability to manage the high volume of tests and research activities during a public health crisis, e.g. sufficient equipment, personnel, resources to meet the surge in demand, etc.
1.4 Supply chains and materials	Challenges affecting availability and reliability of essential supplies and materials, such as reagents, testing kits, and personal protective equipment (PPE), etc. Disruptions that caused significant delays and shortages, impacting laboratory operations.
1.5 Access to data and samples	Challenges affecting availability and ease of obtaining and sharing necessary data and biological samples.
1.6 Coordination and data sharing/standardisation	Challenges affecting mechanisms and protocols for sharing data and coordinating efforts among different laboratories, institutions, etc.
1.7 Other	Any other challenges that do not fall under the other categories.
2. Solutions and Adaptations	
2.1 Supply chains and resources	Actions to improve the availability and reliability of essential supplies and materials, such as reagents, testing kits, and personal protective equipment (PPE), etc.
2.2 Physical infrastructure	Actions to improve and adapt PHL facilities to accommodate increased testing volumes (e.g. new machines) and ensure safe working conditions for staff, etc.
2.3 Staffing and ways of working	Actions to adjust/improve staffing models, training, hiring, etc.
2.4 Lab techniques and procedures	Actions to adopt/improve/integrate new scientific techniques, laboratory procedures, etc.
2.5 Protocols and workflow	Actions to adopt/improve/integrate new standardised protocols (SOPs), mechanisms to ensure consistency, safety, efficiency, etc.
2.6 Technology and digital infrastructure	Actions to adopt/improve/integrate novel technologies, analysis, communication, etc.
2.7 Collaboration	Actions to strengthen collaborations among laboratories, institutions, countries, etc.
2.8 Other	Any other solutions or adaptations.
3. Impacts and Implications	
3.1 Positive	Beneficial outcomes resulting from the adaptations and solutions implemented by laboratories during COVID-19.
3.2 Negative	Adverse outcomes or challenges that persisted despite the efforts made by laboratories during COVID-19.
3.3 Neutral/other	Impacts that were neither distinctly positive nor negative, or those that had mixed outcomes. This category also covers any other implications that do not fit neatly into the positive or negative categories.
4. Sustaining Improvements	
4.1 Lessons	Key insights and best practices learned from the adaptations and responses implemented during COVID-19. These lessons can guide future preparedness and response efforts in public health laboratories.

Category	Details
4.2 What is needed to sustain advances?	Examples like resources, strategies, and policies necessary to maintain and build upon the improvements achieved during COVID-19.
4.3 Were the changes/implementations sustained?	Were the changes and implementations only applied during the COVID-19 pandemic? Were they implemented as permanent solutions?
Potential sources of bias	
Article quality	
Potential interviewees?	
Stage of pandemic	
Other research comments	

Annex 6. Prioritisation criteria (REA)

Topic	High priority	Low priority
Experiences within public health labs in EU/EEA Member States (e.g. national/regional lab networks) -- Descriptions of actual challenges faced, and solutions implemented	Mostly high priority	Articles describing results of surveillance activities (not about laboratory experience, but only reporting results)
Impact of Covid-19 on other surveillance activities	Impact on surveillance for respiratory infectious diseases Reviews, summary articles	Impact on surveillance for other diseases (non-respiratory/non-communicable)
Challenges, solutions and lessons learned	Reviews, summary articles Articles that describe challenges, solutions and lessons not covered in review articles (ensuring coverage across breadth of topics relevant to study scope)	Articles describing challenges, solutions and lessons learned within individual studies or projects, where topic is already well-described in review/summary articles
Clinical and diagnostic labs	Articles about data management and integration (for use in public health activities) Lessons learned about the role of clinical/diagnostic labs in public health activities	Articles about clinical and diagnostic labs with no specific focus on public health activities
Scientific articles describing laboratory techniques and methods that were up-to-date evidence at the time of publishing (e.g. characterising virus, best techniques for laboratories to use	Reviews, summary articles from later in pandemic describing best practices relevant to public health labs Articles that describe specific scientific advances relevant to public labs, which are not covered in review/summary articles (ensuring coverage across breadth of topics relevant to study scope)	Articles from early in the pandemic that are no longer up-to-date Technical articles describing specific techniques for labs (not specific to public health labs – e.g. describing pooled sampling protocols, development of specific diagnostic tests) Articles describing or comparing the technical performance of specific techniques/assays (not in public health-specific context)
Point of care tests, mobile labs and lab-on-chip technologies	Articles about data management and integration (for use in public health activities) Lessons learned about role of point of care tests, mobile labs surveillance in public health activities	Articles about lab-on-chip technologies (prior to point of public health labs being involved) Articles describing the technical performance of specific point of care tests Articles describing processes in mobile health labs (e.g. safety, workflows -- prior to point of public health labs being involved)
Wastewater and environmental surveillance	Articles about data management and integration (for use in public health activities) Lessons learned about role of environmental/wastewater surveillance in public health activities Summaries of environmental/wastewater surveillance across EU/EEA	Technical articles describing best techniques to collect or process samples in environmental/wastewater surveillance (prior to the point of public health labs being involved) Descriptions of specific environmental surveillance activities in EU/EEA Member States

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