UNIWERSYTET
MIKOŁAJA KOPERNIKA
W TORUNIU
Wydział Nauk o Zdrowiu
Collegium Medicum w Bydgoszczy

**Paweł Niewiadomski**

# Ekonomiczne i epidemiologiczne obciążenie umieralnością spowodowaną pandemią COVID-19

**Rozprawa na stopień doktora nauk o zdrowiu**

**Promotorzy:**

**Dr hab. Błażej Łyszczarz, prof. UMK**

**PhD Marta Ortega-Ortega, Associate Professor**

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# Spis treści

## Artykuły włączone do rozprawy

Rozprawę doktorską przygotowano w formie spójnego tematycznie cyklu publikacji, do którego włączono następujące artykuły:

**I**

**Niewiadomski P**, Ortega-Ortega M, Łyszczarz B. Productivity Losses due to Health Problems Arising from COVID-19 Pandemic: A Systematic Review of Population-Level Studies Worldwide. Appl Health Econ Health Policy. 2025;23(2):231-251. doi:10.1007/s40258-024-00935-8

Udział autorski: koncepcja i metodyka badania, zbieranie danych, analiza piśmiennictwa, pisanie manuskryptu, interpretacja wyników, graficzne przedstawienie wyników, korekta manuskryptu.
Punktacja MNiSW: 100
Impact Factor: 3,3

**II**

**Niewiadomski P**, Wojtasik J, Łyszczarz B. Beyond death counts: how COVID-19 affected excess mortality and productive life-years lost across 28 European states, 2020-2023. Front Public Health. 2026;13:1720864. doi:10.3389/fpubh.2025.1720864

Udział autorski: koncepcja i metodyka badania, zbieranie danych, analiza danych, pisanie manuskryptu, interpretacja wyników, graficzne przedstawienie wyników, korekta manuskryptu.
Punktacja MNiSW: 100
Impact Factor: 3,4

**III**

**Niewiadomski P**, Ortega-Ortega M, Łyszczarz B. Paid and unpaid productivity losses across 28 European countries due to excess deaths and COVID-19 deaths from 2020 to 2023. Eur J Health Econ. doi: 10.1007/s10198-026-01916-5

Udział autorski: koncepcja i metodyka badania, zbieranie danych, analiza danych, pisanie manuskryptu, interpretacja wyników, graficzne przedstawienie wyników, korekta manuskryptu.

Punktacja MNiSW: 100

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SYSTEMATIC REVIEW

# Productivity Losses due to Health Problems Arising from COVID-19 Pandemic: A Systematic Review of Population-Level Studies Worldwide

Paweł Niewiadomski[1] · Marta Ortega-Ortega[2] · Błażej Łyszczarz[3]

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## Abstract

**Aim** To systematically review the evidence on productivity losses due to health problems arising from the COVID-19 pandemic based on evidence from population-level studies.

**Methods** Following PRISMA statement, we conducted a systematic review using Medline, Embase, Scopus, Web of Science, EconLit, WHO COVID-19 Research and EuropePMC databases and a grey literature search. We included population-level studies using secondary data and qualitatively assessed eligible studies. For a quantitative cross-study comparison, we calculated losses in 2020 international dollars and as a share of gross domestic product. PROSPERO registration number: CRD42023478059.

**Results** Thirty-eight studies were eligible for review, most of which reported losses in high-income countries and the European region. COVID-19 was a focus of 33 studies while 3 studies investigated losses from both long COVID and excess mortality. The Human Capital Approach dominated (30 studies) and no study used the Friction Cost Approach. Most studies (84%) reported on premature mortality losses and a quarter provided estimates of losses due to absenteeism. Of the 33 studies eligible for quantitative comparison, we found that the productivity losses ranged from 0 to 2.1% of gross domestic product; the greatest losses were in the high-income countries and for those aged 40–59 years; and losses among men contributed to around 3/4 of the total burden.

**Conclusion** The available evidence on the topic is limited, particularly considering the methodological approaches used. Thus, more research is needed to reach a more comprehensive understanding of economy-level productivity losses resulting from the recent COVID-19 pandemic.

## 1 Introduction

Apart from the enormous health burden of COVID-19 [1, 2], the pandemic has had significant economic consequences worldwide, with gross domestic product (GDP) decline, increased unemployment rates, public finance

**Key Points for Decision Makers**

Evidence on pandemic-related productivity losses from morbidity and excess mortality is scarce and requires further investigation.

Productivity losses from COVID-19 are concentrated among those at middle age (40–59 years) and men, pointing to population groups that require policy attention in potential future pandemics.

Short-term evidence prevails and little is known about the long-lasting economic burden of the pandemic.

✉ Błażej Łyszczarz
blazej@cm.umk.pl

1 Doctoral School of Medical and Health Sciences, Nicolaus Copernicus University in Toruń, Bydgoszcz, Poland

2 Department of Applied Economics, Public Economics and Political Economy, Complutense University of Madrid, Madrid, Spain

3 Department of Health Economics, Nicolaus Copernicus University in Toruń, Bydgoszcz, Poland

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deficits, and loss of production capacity [3, 4]. Yet, the pandemic's economic burden extends beyond the general macroeconomic downturn. Health economics research on the impact of COVID-19 focused on healthcare resource utilisation, patient outcomes, the economic burden of inpatients, the impact of non-pharmaceutical interventions (NPIs) on infection rates and population immunity, and productivity losses attributable to the disease (for systematic reviews on the economic aspects of the pandemic, see [5–8]).

Estimation of productivity losses (indirect costs), which represent the potential economic output that was unproduced due to health problems, is a key tool for assessing the economic burden of diseases. These losses encompass costs from both mortality and morbidity, and they are identified as uncompleted production in formal market activities and informal economic production (e.g., housekeeping, volunteering) [9, 10]. Due to its enormous death toll and non-pharmaceutical interventions aimed at limiting the virus spread, COVID-19 plausibly resulted in substantial productivity losses. In an initial 10-week period of the pandemic, nine European states experienced 0.02% (Switzerland) to 0.11% (Spain) GDP loss due to market activities uncompleted as a result of excess mortality [11]. In an Italian study, temporary productivity losses from the pandemic until 28 Apr 2020 were €103 million and the respective losses from COVID-19 mortality were three times higher, reaching 0.17% of the country's GDP [12]. Over a longer period, productivity losses due to COVID-19 in Canada between February 2020 and April 2022 were US$8.3 billion (0.48% of 2019 GDP) [13]. The above figures show a large diversity of loss estimates and are hardly comparable for several reasons. First, as shown above, the period of analysis is diverse across studies and this makes a straightforward comparison of findings difficult. Second, the methods for productivity loss estimations differ and there is no agreement on which of the two commonly used approaches (human capital approach [HCA] or friction cost approach [FCA]) is superior [9]. Eventually, studies using population-level data (like those reported above) provide estimates of losses expressed in macro-measures, e.g., share of GDP lost, while the results from sample-based studies are more contextual and tougher to generalise for whole economies [14].

Previous systematic reviews on the cost of COVID-19 have analysed productivity losses of the pandemic; but they were either limited to specific sub-groups (e.g., healthcare workers [5] or inpatients [15]) or aggregated different categories of costs (e.g. direct costs, indirect costs, out-of-pocket payments [15, 16]). Therefore, earlier reviews have provided a rather broad picture of COVID-19-related cost studies. We intend to take a narrower perspective and analyse a specific topic of productivity losses related to the pandemic and focus solely on population-based studies. The reasoning behind this choice includes the following. Using a relatively homogenous approach (only population-based settings), we intend to compare estimates from all included studies quantitatively. We also aim to compare methodological approaches used for indirect cost estimation and this could be done more thoroughly with a set of studies sharing common characteristics. Moreover, it seems that > 4 years after the inception of the pandemic, there is sufficient evidence to synthesise quantitative evidence on the burden of COVID-19 in terms of whole-economy productivity losses. Eventually, by reviewing the current state of knowledge on the topic, it will be possible to assess whether the evidence on hand will enable policy-makers with valuable insights to inform evidence-based decisions regarding future pandemic preparedness and the magnitude of productivity losses as a part of the overall economic burden of COVID-19 [17, 18].

This is the first study to systematically review the evidence on productivity loss due to health problems arising from the COVID-19 pandemic based on results from population-level studies.

## 2 Methods

This systematic review follows the PRISMA (Preferred Reporting for Systematic Reviews and Meta-Analyses) guidelines for conducting and reporting a systematic review [19]. The protocol for this review was prospectively registered in PROSPERO (registration number CRD42023478059).

### 2.1 Search Strategy and Selection of Studies

A systematic literature search was conducted in Medline (via PubMed), Embase, Scopus, Web of Science, EconLit, WHO COVID-19 Research Database and EuropePMC. The following websites were searched for grey literature: Google, Google Scholar, EconPapers, the National Bureau of Economic Research, the Organization for Economic Co-operation and Development, the Office of Health Economics, and the World Bank. The primary search query was developed for the PubMed search engine by authors Błażej Łyszczarz and Paweł Niewiadomski and were subsequently assessed by a librarian expert for accuracy and quality. The Systematic Review Accelerator (Polyglot tool; sr-accelerator.com/#/polyglot), maintained by the Institute for Evidence-Based Healthcare at Bond University, was used to translate a query from PubMed to other databases used in literature search, except for EconLit. Marta Ortega-Ortega developed a search syntax for the EconLit database. Keywords used for identifying concepts of COVID-19 and productivity losses are exhibited in Table 1 while detailed queries are shown in Online Resource 1.

The Rayyan online application (rayyan.ai) was used for the deduplication process. In the first stage of duplicate removal, we used a 95% similarity criterion, then deduplication was based on titles, DOI numbers and pages in the outlet (in the above order and each stage separately). The deduplication of the remaining part of the articles was resolved manually. The screening was performed manually using the Rayyan application. Błażej Łyszczarz and Paweł Niewiadomski independently (blind mode on) examined the titles and abstracts of potentially relevant articles. Disagreements were resolved by discussion between the two reviewers.

Subsequently, Błażej Łyszczarz and Paweł Niewiadomski reviewed full texts of the relevant studies based on the eligibility criteria and the systematic review objectives. We used backward citation tracking (reference lists of studies eligible for full-text analysis) and forward citation tracking (publications that cite studies eligible for full-text analysis, as reported in Google Scholar) to identify other studies that met the eligibility criteria. The citation tracking applied to (1) studies initially included based on database searches and initial screening of titles and abstracts; (2) studies initially included based on citation tracking of included studies (3) studies initially included based on citation tracking of systematic reviews on economic aspects of COVID-19 identified through database and hand searching; and (4) studies initially included based on hand searching of Google, Google Scholar, technical reports and organisations' websites. Online Resource 1 contains search queries, a strategy for searching grey literature, the number of hits per line in the Embase search, a list of studies included in the final analysis and a list of excluded studies after full-text analysis, together with the reasons for their exclusion.

We searched publications from 1 Nov 2019 to 19 Dec 2023.

### 2.2 Inclusion and Exclusion Criteria

The review included published studies meeting the following criteria: secondary, population-level quantitative studies using all methods that estimate productivity losses resulting from the COVID-19 pandemic. We focused primarily on evidence assessing losses directly attributable to health problems (mortality and morbidity) but also included losses arising from indirect pandemic impacts, such as lockdowns or quarantines. The following studies were excluded: studies limited to particular sub-populations (e.g., inpatients, outpatients, and workers) or economic sectors/industries, qualitative studies, editorials, commentaries, views, opinions, letters, and dissertations. Yet, to account for potential publication bias [20], we included preprints and unreviewed publications in our review.

Studies using the value of statistical life (VSL) concept to determine the monetary value of lives lost due to the pandemic [21, 22] are not eligible for this review. This is because the VSL is conceptually different from the productivity losses methodology and estimates from these two approaches are incomparable.

The review included studies published in English, Spanish, or Polish language.

### 2.3 Data Extraction

Pawel Niewiadomski designed forms for qualitative and quantitative data extraction. The forms were pilot-tested by extracting data from eight randomly selected studies (Błażej Łyszczarz and Paweł Niewiadomski). Subsequently, several corrections were made to the forms based on the extraction process tests.

Eventually, we extracted the following qualitative information from eligible studies: first author and publication year; title; study design; period of analysis; reference year; geographical settings; country classifications by income (World Bank) and by region (WHO regional offices); currency; main data sources; study population; diagnosis; loss estimation approach; losses categories; discounting;

**Table 1** Keywords used for search queries

| |
|---|
| *Keywords for 'COVID-19':* |
| covid-19, covid19, covid-2019, covid2019, coronavirus disease 2019, coronavirus disease 19, sars-cov-2, cov 2, cov2, severe acute respiratory syndrome coronavirus 2, SARS coronavirus 2, 2019-nCoV, 2019nCoV, 2019 novel coronavirus, ncov, novel cov, hCoV-19, pandemic, postcovid, longcovid, postcoronavirus, postsars |
| *Keywords for 'productivity losses':* |
| productivity loss*, productivity lost, productivity cost*, production loss*, production lost, lost productivity, lost production, labour productivity, labor productivity, indirect cost*, economic cost*, economic burden, economic loss*, financial loss*, cost of illness, burden of illness, illness cost*, illness burden, sickness cost*, cost* of sickness, disease cost*, cost* of disease, absenteeism, presenteeism, mortality burden, morbidity burden, burden of mortality, burden of morbidity, human capital, friction, intangible cost*, caregiv* burden, burden of caregiv* |

perspective; productivity measure used; results reported; sensitivity analysis; study limitations; and authors' conflict of interest (more details explaining contents of the categories in Online Resource 2). For the quantitative data, we extracted raw estimates on the productivity losses for each study meeting inclusion criteria. Only those studies reporting sufficiently detailed figures needed for cross-study comparison were included in the quantitative analysis (see 'Quality assessment' sub-section below).

Błażej Łyszczarz and Paweł Niewiadomski extracted qualitative data from the included studies and each cross-checked the accuracy of the data extraction made by the other reviewer. Pawel Niewiadomski performed quantitative data extraction, estimated quantitative figures reported, and Błażej Łyszczarz cross-checked the data and results obtained. Completed quality and quantity forms are available in the Online Resources. The resultant quantitative form was used for a cross-study comparison of losses using common currency (International dollar—Int$) and common year (2020) (for more details on the approach used see the Sect. 2.5). These estimates, together with formulas for their calculation, are presented in detail in Online Resource 3 for each eligible study.

### 2.4 Quality Assessment

The tool designed by Stunhldreher et al [23], which has recently been used in a systematic review focusing specifically on productivity losses [24], was used to assess the quality of the eligible studies. Two reviewers (Błażej Łyszczarz and Paweł Niewiadomski) carried out the qualitative assessment independently and any disagreements were resolved by the third reviewer (Marta Ortega-Ortega). The checklist was adapted to our study design of interest (population-level settings) and we used the following categories: (1) Study objective; (2) Disease and diagnostic criteria; (3) Cost description; (4) Currency; (5) Reference year; (6) Perspective; (7) Cost incorporated from more than one category; (8) Data source; (9) Valuation of costs; (10) Discounting; (11) Sensitivity analyses; (12) Results discussed with respect to other studies; (13) Limitations discussed; (14) Conclusion appropriate regarding uncertainty of results. For each of the above criteria, the exclusive assessment choices were (a) yes or (b) no/not clear. The resulting percentage of positive answers yielded a quality assessment score for the studies included.

### 2.5 Approach to Cross-Study Comparison of Quantitative Results

For the cross-study comparison of productivity losses, we used the following approach. First, we extracted quantitative data from eligible studies and excluded those without sufficiently detailed figures. Second, to compare losses across time and different currencies used, and to express losses as a share of GDP, we used the International Monetary Fund's (IMF) data on inflation rates, purchasing power parities and GDP [25]. For some studies, the currency used originally was Int$ and in these cases, we only adjusted for inflation using 2020 as a base year. For those studies that reported findings in local currencies, we used the IMF conversion rates to express losses in Int$ and adjusted for inflation as explained above. For some studies that deal with provincial loss estimation, regional input data on GDP were obtained from other sources, as shown in Online Resource 3. Third, to account for the fact that several studies reported loss estimates for periods other than full years, in calculating shares of GDP lost, we used a respective GDP proportion; e.g. an Italian study [12] analysed the period 21 Feb 2020 to 28 Apr 2020 (68 days), therefore, we used 68/366 share of the country's GDP. Fourth, to make results more comparable across time, we annualised losses reported in original studies. This involved dividing the loss incurred during a given period by the duration of that period (expressed in years) and resulting annualised figures represent the equivalent yearly losses. Additionally, several studies did not report a starting period of analysis and, in such cases, we assumed the day of the first COVID-19 case in the country to be the starting date of the analysis. Fifth, to allow for more accurate cross-study comparison, we adjusted age categories as reported in the source studies to three bands, 0–39 years; 40–59 years and 60+ years. This was done by assuming an equal distribution of losses across all single ages in particular intervals in source studies, e.g., for an age band 31–45 years reported originally in the study analysed, we assigned 9/15 of the loss to interval 0–39 years and 6/15 part to interval 40–59 years. All the detailed adjustments used for the cross-study comparison of losses are shown in Online Resource 3, separately for each study included.

## 3 Results

### 3.1 Searching and Study Selection Results

As a result of the database search, we identified 15,588 records. A total of 9621 records were removed within the deduplication process. We selected 52 studies for a full-text assessment. Finally, 22 of these met the eligibility criteria. Identification of studies through alternative methods, such as searching grey literature and citation tracking, resulted in 4188 identified records and, after the initial screening process, 87 items were selected for full-text analysis. Based on this stage, 16 articles were eligible for inclusion in the review. Eventually, 38 studies met the inclusion criteria; among the studies identified, we included two preprints [26, 27] and one unreviewed publication [28]. Detailed information on the study selection process is depicted in Figure 1 using a PRISMA diagram.

### 3.2 Characteristics of Eligible Studies

Table 2 summarises the qualitative characteristics of the studies included in the analysis. Half of the studies ($n = 19$) focus on high-income countries while only two provide estimates from low-income countries. However, some studies report results for multiple countries [11, 29–31] and, when these are accounted for, around one-third of unique country-specific estimates come from high-income and lower-middle-income states each. Considering the regions of the WHO, 34% ($n = 13$) of the articles report findings from Europe and 21% percent ($n = 8$) from both the Americas and South-East Asia. However,, because one study estimated losses for 54 African countries [29], more than half of single estimates are from Africa. The countries analysed in the highest number of articles were India ($n = 8$); the USA ($n = 5$); Canada, Germany and Italy ($n = 3$ each). Interestingly, for India, half of the articles focused on single regions, not the whole country. COVID-19 itself was a focus of 33 included articles, while three studies dealt with either long COVID or excess all-cause deaths. For 30 studies, the human capital approach was used to estimate losses, in eight papers the method was not explicitly mentioned and one study used the proxy good approach to estimate losses from non-market activities [11]. Considering the productivity measures used, 61% of articles ($n = 23$) relied on a GDP-based approach, 39% ($n = 15$) used income- or earning-based measures and two articles did not provide details in this respect [28, 32]. The vast majority of studies included in the review estimated losses resulting from premature mortality (84%; $n = 32$) and about a quarter reported on absenteeism costs. Eventually, more than half of the studies ($n = 22$) applied sensitivity analysis to analyse how the results change with model assumptions/input data variations (Table 2).

### 3.3 Quality Assessment of Included Studies

Of the 38 studies included in the review, none met all the 14 quality criteria. Two of the studies were assessed as of the highest quality meeting > 90% of the criteria [27, 33]. For six studies [11, 29, 34–37] the quality score was high and ranged from 80% to 89%. A majority of included studies (22 of 38) [12, 13, 26, 31, 38–55] met 70–79% of the quality criteria. In three studies [32, 56, 57], we identified

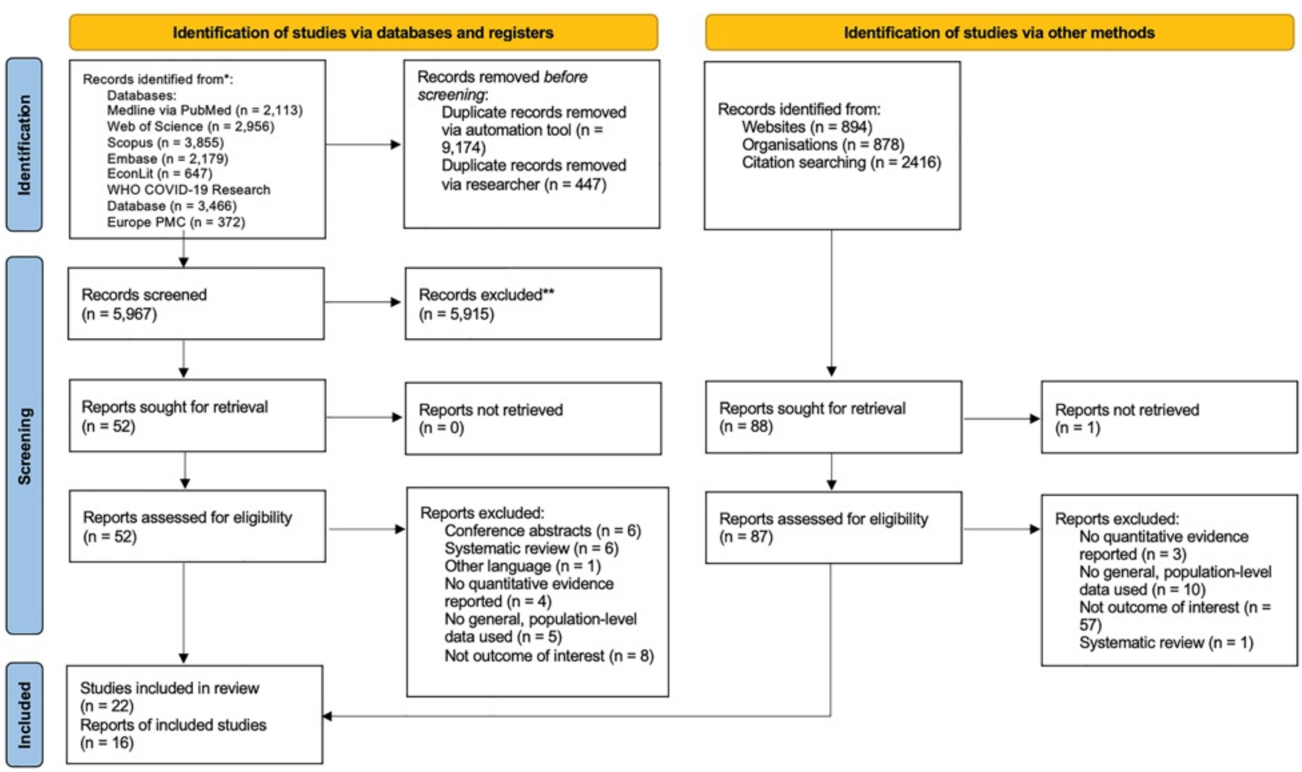


**Fig. 1** PRISMA (Preferred Reporting Items for Systematic review and Meta-Analysis) flow diagram for the study selection process

**Table 2** Summary characteristics of studies included in the systematic review (N = 38)

| Study characteristic | Articles |
|---|---|
| *World Bank classification* | *N* = 38 |
| High income | 19 (50%) |
| Upper-middle income | 10 (26%) |
| Lower-middle income | 12 (32%) |
| Low-income | 2 (5%) |
| *World Health Organization region* | *N* = 38 |
| Africa | 5 (13%) |
| Americas | 8 (21%) |
| Eastern Mediterranean | 1 (3%) |
| Europe | 13 (34%) |
| South-East Asia | 8 (21%) |
| Western Pacific | 5 (13%) |
| *Countries/regions* | *N* = 38 |
| India | 8 (21%) |
| USA | 5 (13%) |
| Canada, Germany, Italy | 3 (8%) |
| China, France, Kenya, Madagascar, Mauritius, South Africa, Spain, Sweden, Turkey | 2 (5%) |
| 66 countries/regions (not listed separately here) | 1 (3%) |
| *Diagnosis* | *N* = 38 |
| COVID-19 | 33 (87%) |
| Long COVID | 3 (8%) |
| All-cause excess mortality | 3 (8%) |
| *Losses estimation approach* | *N* = 38 |
| Human capital approach | 30 (79%) |
| Proxy good approach | 1 (3%) |
| Not specified/unclear | 8 (21%) |
| *Productivity measure used* | *N* = 38 |
| Average income or earnings-based | 15 (39%) |
| Average GDP based | 23 (61%) |
| Not reported | 2 (5%) |
| *Loss categories* | *N* = 38 |
| Premature mortality | 32 (84%) |
| Absenteeism | 11 (26%) |
| Quarantine/lockdown/cases | 2 (5%) |
| *Sensitivity analysis for losses estimates* | *N* = 38 |
| Yes | 22 (58%) |
| No | 16 (42%) |

For the column 'Articles' the percentages in some categories do not add up to 100% because some studies are counted more than once as they report estimates from more than one category

a low-quality score of 60–69% and another five studies [28, 30, 58–60] were judged as being the lowest-quality analyses with a score of < 60%. The quality assessment (broken down into five sub-categories evaluated) is depicted in Fig. 2 while the detailed results for each criterion are shown in Online Resource 4.

### 3.4 Cross-Study Comparison of Productivity Losses

We compared findings from eligible studies regarding productivity losses resulting from the pandemic. Table 3 presents comparative results for eligible studies and the magnitude of losses for each cost category, expressed in international dollars and deflated to a common year (2020Int$). In 33 included studies, we identified 96 separate estimates for a single country/region.

The highest productivity losses of Int$623 billion (10.36% of GDP) were identified in a Chinese study analysing COVID-19 losses from partial lockdown, premature mortality and cases in the first quarter of 2020 [33]. However, we shall underline that 99.9% of the losses estimated in this study were due to partial lockdown; therefore, virtually the entire economic burden identified here arises not from the direct health impact of COVID-19, but rather from the indirect effects of NPIs applied. The other studies that reported losses of >0.5% of GDP were those from India, 0.58% [36]; Spain, 0.53% [11] (both using the excess mortality approach); four papers by Kirigia et al that used life expectancy as an upper bound of age in loss estimation in COVID-19 mortality (Spain, 2.12% [34]; the UK, 0.80% [40]; Italy, 0.96% [46]; and France, 0.54% [47]); and a study of long COVID costs related to absenteeism in the USA (an upper range of estimate identified was 0.72% of GDP) [56]. On the other hand, in three countries no losses were identified and this applies to the excess mortality analysis of Germany until 15 May 2020 [11] and to Eritrea and Seychelles until 1 Aug 2020 in terms of COVID-19 premature mortality [29]. In general, 2/3 of 96 single estimates of the share of GDP lost were below 0.1% of GDP, 17 estimates were within a range of 0.1–0.2%, four estimates were between 0.2% and 0.3% of GDP and three estimates were between 0.3% and 0.4% of GDP. More than 0.5% of lost GDP was identified for six studies and two of these estimates were > 1% of GDP (these figures refer to total losses, not single cost categories from studies where more than one category was estimated; for details see Table 3). Per death losses were the highest in the Spanish study [34], which estimated a cost of Int$470,798 per death. The respective estimates were > Int$300,000 in Switzerland [11], China [54], Italy [46], France [47], Mauritius [29, 52] and Canada [13]. Notably, all these results, apart from the Swiss and Canadian estimates, were produced using a uniform methodology and by a team led by the same author. On the other hand, for several African countries, per death losses were lower than Int$10,000 [29]. It is clear that per absence case losses were lower than those in mortality and ranged from Int$76 in the Indian state of West Bengal [38] to Int$1604 in Canada [13]. For annualised total productivity losses, the highest economic burden (apart from the outlier Chinese study of

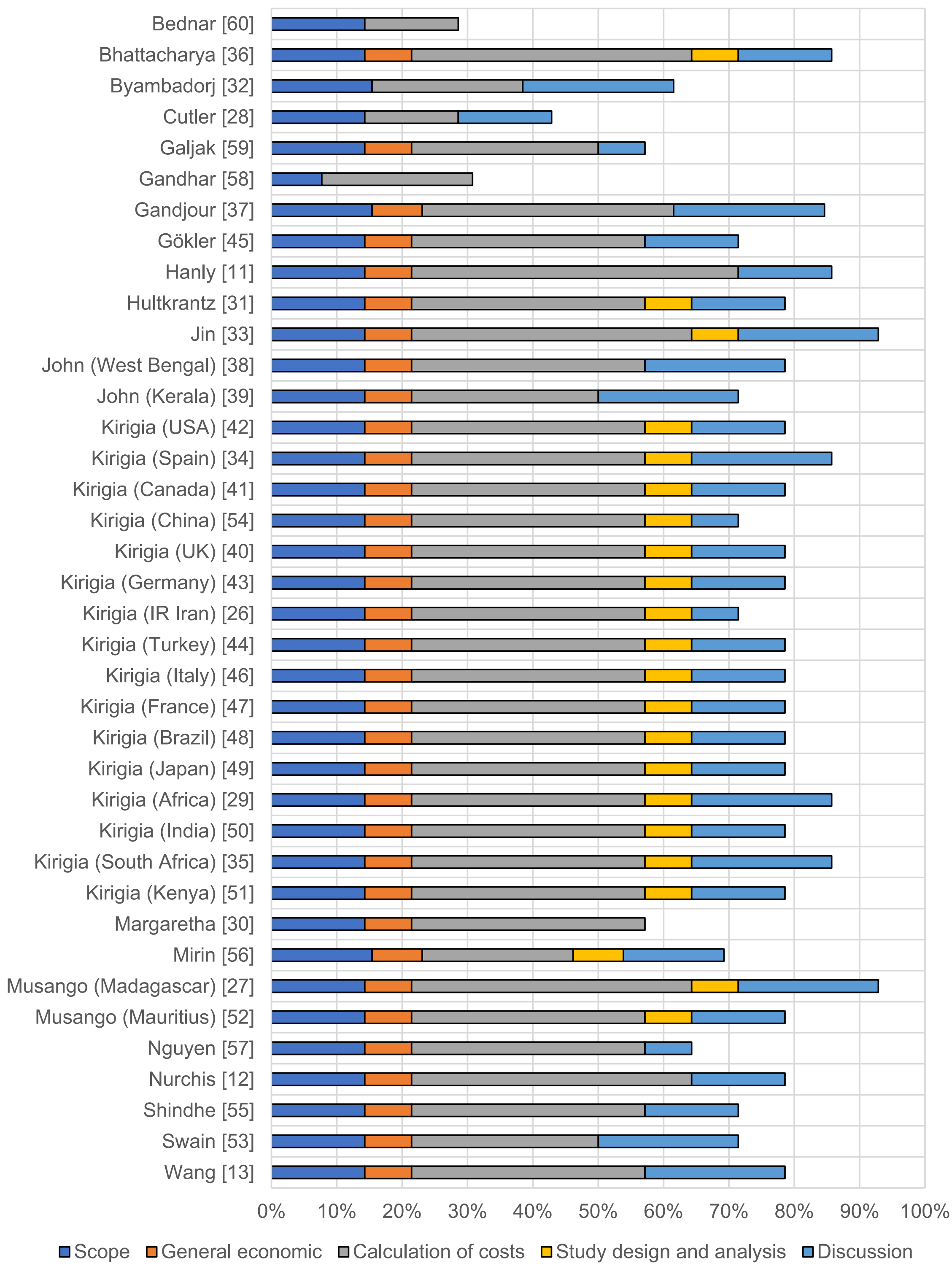


**Fig. 2** Results of quality assessment of studies included in the review. Labels for particular studies contain the first author's name and reference to the bibliography. In quality assessment, a tool developed by Stuhldreher et al. [23] was used. The tool consists of 22 items organised into 5 groups (scope; general economic; calculation of costs; study design and analysis; and discussion) but only some were used. Specifically, because this review focuses on population-level studies solely, we excluded assessment items that are specific to sample-based settings, i.e., inclusion and exclusion criteria; non-diseased comparison group or disease-specific costs; missing data and imputation method; statistics appropriate; sample size (subgroup); demographics (minimum age and sex); arithmetic mean cost; standard deviations (SDs, errors). In total, 14 of 22 items were used for assessment. For four papers [32, 37, 56, 58], 13 items were assessed because discounting was not applicable for these studies (one-year or shorter time horizon). The detailed results of the quality assessment are reported in Online Resource 4. Referencing details for labels used in the figure are shown in Table 3

**Table 3** Overview of the studies' main characteristics and results

| First author [reference] | Location (period of analysis[a]; dd/mm/yy) | Disease definition | Loss category | Productivity losses (2020 Int$[b]) | Productivity losses: as % /per case (2020 Int$) | Annualised productivity losses (2020 Int$) | Share of total losses (%) | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Age-specific losses | Sex-specific losses |
| Bhattacharya [36] | West Bengal (India) (17/03/2020–31/12/2022) | COVID-19 | Premature mortality | 899,065,811 | 0.057/55,171 | 321,974,645 | 0–39 y: 21%<br>40–59 y: 56%<br>60+ y: 23% | Males: 60%<br>Females: 40% |
| | | Excess all-cause mortality | | 9,224,432,810 | 0.583/55,174 | 3,303,466,153 | 0–39 y: 21%<br>40–59 y: 56%<br>60+ y: 23% | Males: 60%<br>Females: 40% |
| Byambadorj [32] | Mongolia (22/01/2020–3/09/2020) | COVID-19 | Total | 26,996,257 | 0.108 | 43,719,603 | NA | NA |
| | | | Partial lockdown | 26,572,538 | 0.106/435 | 43,033,403 | | |
| | | | Cases | 423,719 | 0.002/1,367 | 686,200 | | |
| Gandjour [37] | Germany (2021) | Long COVID | Absenteeism | 4,458,503,094 | 0.093/not calculable | 4,458,503,094 | NA | NA |
| Gökler [45] | Turkey (11/03/2020–31/12/2020) | COVID-19 | Premature mortality | 846,076,489 | 0.041/26,393 | 1,049,708,458 | NA | Males: 79%<br>Females: 21% |
| Hanly [11] | Belgium (9/03/2020–15/05/2020) | Excess all-cause mortality | Premature mortality | 262,023,884 | 0.235/158,625 | 1,410,305,023 | NA | Males: 79%<br>Females: 21% |
| | France (2/03/2020–1/05/2020) | | | 826,215,468 | 0.164/150,644 | 4,957,292,808 | | Males: 66%<br>Females: 34% |
| | Germany (2/03/2020–15/05/2020) | | | 0 | 0.000/- | 0 | | Males: 0%<br>Females: 0% |
| | Italy (9/03/2020–1/05/2020) | | | 588,356,772 | 0.162/83,455 | 3,987,751,451 | | Males: 92%<br>Females: 8% |
| | Netherlands (9/03/2020–15/05/2020) | | | 450,907,823 | 0.242/173,164 | 2,426,945,050 | | Males: 92%<br>Females: 8% |
| | Portugal (9/03/2020–1/05/2020) | | | 40,070,104 | 0.078/107,751 | 271,586,263 | | Males: 59%<br>Females: 41% |
| | Spain (9/03/2020–15/05/2020) | | | 1,792,698,856 | 0.534/159,647 | 9,648,937,963 | | Males: 72%<br>Females: 28% |
| | Sweden (9/03/2020–5/05/2020) | | | 126,645,228 | 0.120/127,850 | 681,649,316 | | Males: 99%<br>Females: 1% |
| | Switzerland (9/03/2020–15/05/2020) | | | 51,382,389 | 0.044/353,877 | 276,558,155 | | Males: 65%<br>Females: 35% |
| Jin [33] | China (01/01/2020–31/03/2020) | COVID-19 | Total | 623,585,647,558 | 10.365 | 2,508,047,769,301 | NA | NA |
| | | | Premature mortality | 424,833,687 | 0.007/227,305 | 1,708,671,753 | | |
| | | | Cases | 92,979,476 | 0.002/2,105 | 373,961,410 | | |
| | | | Partial lockdown | 623,067,834,395 | 10.357/1,496 | 2,505,965,136,138 | | |

**Table 3** (continued)

| First author [reference] | Location (period of analysis[a]; dd/mm/yy) | Disease definition | Loss category | Productivity losses (2020 Int$[b]) | Productivity losses: as % /per case (2020 Int$) | Annualised productivity losses (2020 Int$) | Share of total losses (%) | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Age-specific losses | Sex-specific losses |
| John [38] | West Bengal (India) (until 07/01/2022) | COVID-19 | Total | 277,585,686 | 0.026 | 143,696,754 | 0–39 y: 36%<br>40–59 y: 64% | Males: 81%<br>Females: 19% |
| | | | Premature mortality | 147,533,701 | 0.014/7,427 | 76,373,225 | 0–39 y: 25%<br>40–59 y: 75% | Males: 85%<br>Females: 15% |
| | | | Absenteeism | 130,051,985 | 0.012/76 | 67,323,530 | 0–39 y: 48%<br>40–59 y: 52% | Males: 77%<br>Females: 23% |
| John [39] | Kerala (India) (30/01/2020–10/06/2021) | COVID-19 | Total | 630,564,364 | 0.125 | 463,016,711 | 0–39 y: 51%<br>40–59 y: 49% | Males: 86%<br>Females: 14% |
| | | | Premature mortality | 73,857,811 | 0.015/23,052 | 54,233,006 | 0–39 y: 29%<br>40–59 y: 71% | Males: 84%<br>Females: 16% |
| | | | Absenteeism | 556,706,553 | 0.111/257 | 408,783,706 | 0–39 y: 54%<br>40–59 y: 46% | Males: 86%<br>Females: 14% |
| Kirigia [42] | USA (until 03/05/2020) | COVID-19 | Premature mortality | 19,780,290,990 | 0.347/292,889 | 73,127,136,388 | 0–39 y: 9%<br>40–59 y: 41%<br>60+ y: 50% | NA |
| Kirigia [34] | Spain (until 19/04/2020) | COVID-19 | Premature mortality | 9,629,234,112 | 2.122/470,798 | 38,307,605,272 | 0–39 y: 14%<br>40–59 y: 45%<br>60+ y: 41% | NA |
| Kirigia [41] | Canada (until 16/07/2020) | COVID-19 | Premature mortality | 2,037,021,173 | 0.231/231,217 | 4,309,536,123 | 0–39 y: 2%<br>40–59 y: 11%<br>60+ y: 87% | NA |
| Kirigia [54] | China (until 24/02/2020) | COVID-19 | Premature mortality | 924,346,794 | 0.025/356,203 | 6,151,107,756 | 0–39 y: 38%<br>40–59 y: 44%<br>60+ y: 18% | NA |
| Kirigia [40] | United Kingdom (until 2/07/2020) | COVID-19 | Premature mortality | 9,883,426,226 | 0.802/225,104 | 23,798,249,992 | 0–39 y: 3%<br>40–59 y: 22%<br>60+ y: 75% | NA |
| Kirigia [43] | Germany (27/01/2020–8/11/2020) | COVID-19 | Premature mortality | 1,916,725,559 | 0.053/167,619 | 2,444,325,974 | 0–39 y: 3%<br>40–59 y: 24%<br>60+ y: 73% | NA |
| Kirigia [26] | Islamic Republic of Iran (until 11/04/2020) | COVID-19 | Premature mortality | 436,275,007 | 0.245/103,090 | 3,258,707,195 | 0–39 y: 10%<br>40–59 y: 42%<br>60+ y: 48% | NA |
| Kirigia [44] | Turkey (until 15/06/2020) | COVID-19 | Premature mortality | 1,098,469,122 | 0.170/228,514 | 4,323,007,512 | 0–39 y: 8%<br>40–59 y: 36%<br>60+ y: 56% | NA |

**Table 3** (continued)

| First author [reference] | Location (period of analysis[a]; dd/mm/yy) | Disease definition | Loss category | Productivity losses (2020 Int$[b]) | Productivity losses: as % /per case (2020 Int$) | Annualised productivity losses (2020 Int$) | Share of total losses (%) | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Age-specific losses | Sex-specific losses |
| Kirigia [46] | Italy (31/01/2020–20/08/2020) | COVID-19 | Premature mortality | 13,070,141,189 | 0.956/369,088 | 23,564,885,099 | 0–39 y: 1%<br>40–59 y: 9%<br>60+ y: 90% | NA |
| Kirigia [47] | France (until 14/09/2020) | COVID-19 | Premature mortality | 10,492,290,194 | 0.544/339,381 | 16,481,451,549 | 0–39 y: 3%<br>40–59 y: 17%<br>60+ y: 81% | NA |
| Kirigia [48] | Brazil (25/02/2020–07/06/2020) | COVID-19 | Premature mortality | 3,591,028,163 | 0.363/99,629 | 11,529,090,418 | 0–39 y: 10%<br>40–59 y: 42%<br>60+ y: 48% | NA |
| Kirigia [49] | Japan (16/01/2020–29/10/2020) | COVID-19 | Premature mortality | 496,463,298 | 0.012/286,973 | 630,922,108 | 0–39 y: 2%<br>40–59 y: 12%<br>60+ y: 86% | NA |
| Kirigia [29] | Algeria (until 01/08/2020) | COVID-19 | Premature mortality | 245,299,956 | 0.119/202,727 | 582,985,610 | NA | NA |
| | Angola (until 01/08/2020) | | | 2,020,078 | 0.003/38,848 | 6,213,013 | | |
| | Benin (until 01/08/2020) | | | 643,835 | 0.004/17,884 | 1,771,756 | | |
| | Botswana (until 01/08/2020) | | | 297,052 | 0.003/148,526 | 913,622 | | |
| | Burkina Faso (until 01/08/2020) | | | 545,968 | 0.003/10,301 | 1,427,316 | | |
| | Burundi (until 01/08/2020) | | | 3335 | <0.001/3,335 | 10,257 | | |
| | Cameroon (until 01/08/2020) | | | 6,768,581 | 0.016/17,311 | 16,852,385 | | |
| | Cape Verde (until 01/08/2020) | | | 1,962,141 | 0.142/85,310 | 5,399,576 | | |
| | Central African Republic (until 01/08/2020) | | | 113,916 | 0.006/1,931 | 297,809 | | |
| | Chad (until 01/08/2020) | | | 512,961 | 0.005/6,839 | 1,411,607 | | |
| | Comoros (until 01/08/2020) | | | 118,955 | 0.017/16,994 | 478,434 | | |
| | Cote d'Ivoire (until 01/08/2020) | | | 1,757,306 | 0.003/17,228 | 4,594,100 | | |
| | Democratic Republic of Congo (until 01/08/2020) | | | 848,346 | 0.002/3,946 | 2,217,819 | | |
| | Djibouti (until 01/08/2020) | | | 2,375,995 | 0.119/40,965 | 6,538,452 | | |
| | Egypt (until 01/08/2020) | | | 697,921,220 | 0.112/145,249 | 1,520,471,229 | | |
| | Equatorial Guinea (until 01/08/2020) | | | 6,520,729 | 0.067/78,563 | 17,047,049 | | |
| | Eritrea (until 01/08/2020) | | | 0 | 0.000/- | 0 | | |
| | Ethiopia (until 01/08/2020) | | | 5,155,489 | 0.005/18,816 | 13,477,921 | | |
| | Gabon (until 01/08/2020) | | | 6,766,041 | 0.053/138,082 | 17,688,364 | | |
| | Gambia (until 01/08/2020) | | | 135,573 | 0.007/15,064 | 373,081 | | |

**Table 3** (continued)

| First author [reference] | Location (period of analysis[a]; dd/mm/yy) | Disease definition | Loss category | Productivity losses (2020 Int$[b]) | Productivity losses: as % /per case (2020 Int$) | Annualised productivity losses (2020 Int$) | Share of total losses (%) | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Age-specific losses | Sex-specific losses |
| | Ghana (until 01/08/2020) | | | 7,661,250 | 0.011/42,095 | 20,028,696 | | |
| | Guinea (until 01/08/2020) | | | 573,643 | 0.004/12,471 | 1,499,667 | | |
| | Guinea-Bissau (until 01/08/2020) | | | 211,655 | 0.014/8,141 | 614,807 | | |
| | Kenya (until 01/08/2020) | | | 9,543,972 | 0.010/27,988 | 24,950,670 | | |
| | Lesotho (until 01/08/2020) | | | 119,827 | 0.010/9,217 | 569,567 | | |
| | Liberia (until 01/08/2020) | | | 607,756 | 0.023/8,103 | 1,672,471 | | |
| | Libya (until 01/08/2020) | | | 7,111,555 | 0.019/96,102 | 20,657,374 | | |
| | Madagascar (until 01/08/2020) | | | 1,366,586 | 0.009/12,892 | 3,760,680 | | |
| | Malawi (until 01/08/2020) | | | 795,628 | 0.008/6,979 | 2,447,058 | | |
| | Mali (until 01/08/2020) | | | 1,358,740 | 0.008/10,958 | 3,946,816 | | |
| | Mauritania (until 01/08/2020) | | | 4,776,900 | 0.049/30,426 | 12,488,181 | | |
| | Mauritus (until 01/08/2020) | | | 3,071,846 | 0.031/307,185 | 8,453,351 | | |
| | Morocco (until 01/08/2020) | | | 42,956,126 | 0.036/145,249 | 106,951,987 | | |
| | Mozambique (until 01/08/2020) | | | 72,363 | 0.001/6,578 | 210,197 | | |
| | Namibia (until 01/08/2020) | | | 617,442 | 0.007/61,744 | 1,614,170 | | |
| | Niger (until 01/08/2020) | | | 393,189 | 0.003/5,698 | 1,082,009 | | |
| | Nigeria (until 01/08/2020) | | | 14,222,523 | 0.003/16,180 | 33,801,581 | | |
| | Republic of Congo (until 01/08/2020) | | | 2,371,749 | 0.027/43,921 | 6,200,430 | | |
| | Rwanda (until 01/08/2020) | | | 107,243 | 0.001/21,449 | 280,364 | | |
| | Sao Tome and Principe (until 01/08/2020) | | | 454,147 | 0.183/30,276 | 1,484,088 | | |
| | Senegal (until 01/08/2020) | | | 6,151,990 | 0.026/30,010 | 15,317,200 | | |
| | Seychelles (until 01/08/2020) | | | 0 | 0.000/- | 0 | | |
| | Sierra Leone (until 01/08/2020) | | | 282,867 | 0.006/4,222 | 869,994 | | |
| | Somalia (until 01/08/2020) | | | 220,060 | 0.002/2,366 | 605,579 | | |
| | South Africa (until 01/08/2020) | | | 602,528,301 | 0.188/75,269 | 1,500,172,505 | | |
| | South Sudan (until 01/08/2020) | | | 266,490 | 0.015/5,793 | 870,851 | | |
| | Sudan (until 01/08/2020) | | | 18,189,513 | 0.026/24,383 | 47,552,584 | | |
| | Eswatini (until 01/08/2020) | | | 2,073,934 | 0.052/50,584 | 5,421,856 | | |
| | Tanzania (until 01/08/2020) | | | 482,046 | 0.001/22,955 | 1,326,533 | | |
| | Togo (until 01/08/2020) | | | 172,506 | 0.002/9,079 | 429,505 | | |
| | Tunisia (until 01/08/2020) | | | 8,062,957 | 0.016/161,259 | 20,075,117 | | |

**Table 3** (continued)

| First author [reference] | Location (period of analysis[a]; dd/mm/yy) | Disease definition | Loss category | Productivity losses (2020 Int$[b]) | Productivity losses: as % /per case (2020 Int$) | Annualised productivity losses (2020 Int$) | Share of total losses (%) | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Age-specific losses | Sex-specific losses |
| | Uganda (until 01/08/2020) | | | 44,136 | <0.001/14,712 | 121,457 | | |
| | Zambia (until 01/08/2020) | | | 3,527,856 | 0.015/23,363 | 9,708,235 | | |
| | Zimbabwe (until 01/08/2020) | | | 8,666,496 | 0.075/12,933 | 23,849,154 | | |
| Kirigia [50] | India (30/01/2020–3/10/2020) | COVID-19 | Premature mortality | 8,163,602,456 | 0.132/80,928 | 12,047,897,173 | 0–39 y: 28%<br>40–59 y: 56%<br>60+ y: 16% | NA |
| Kirigia [35] | South Africa (05/03/2020–30/05/2022) | COVID-19 | Premature mortality | 6,693,609,607 | 0.364/120,501 | 3,089,358,280 | 0–39 y: 30%<br>40–59 y: 63%<br>60+ y: 7% | NA |
| Kirigia [51] | Kenya (12/03/2020–25/07/2022) | COVID-19 | Premature mortality | 234,984,047 | 0.038/41,443 | 99,132,886 | 0–39 y: 31%<br>40–59 y: 44%<br>60+ y: 25% | NA |
| Mirin [56] | USA (until 25/06/2022) | Long COVID | Absenteeism | 89,346,544,196 – 380,386,277,272 | 0.169–0.721/not calculable | 37,013,575,916 – 157,582,550,929 | NA | NA |
| Musango [27] | Madagascar (20/03/2020–03/03/2023) | COVID-19 | Premature mortality | 36,756,807 | 0.028/25,848 | 12,442,995 | 0–39 y: 71%<br>40–59 y: 26%<br>60+ y: 3% | NA |
| Musango [52] | Mauritius (18/03/2020–16/10/2020) | COVID-19 | Premature mortality | 3,120,689 | 0.007/312,069 | 5,362,311 | 0–39 y: 22%<br>40–59 y: 52%<br>60+ y: 26% | NA |
| Nguyen [57] | Idaho (USA) (2020–2021) | COVID-19 | Total | 200,197,192 | 0.114 | 103,784,947 | NA | NA |
| | | | Premature mortality | 114,211,828 | 0.065/118,354 | 59,208,964 | | |
| | | | Absenteeism | 85,985,365 | 0.049/not calculable | 44,575,982 | | |
| Nurchis [12] | Italy (21/02/2020–28/04/2020) | COVID-19 | Total | 600,570,967 | 0.131 | 3,232,484,911 | 0–39 y: 8%<br>40–59 y: 51%<br>60+ y: 41% | NA |
| | | | Premature mortality | 447,306,407 | 0.098/113,934 | 2,407,560,954 | 0–39 y: 4%<br>40–59 y: 49%<br>60+ y: 47% | |
| | | | Absenteeism | 153,264,560 | 0.033/1,382 | 824,923,957 | 0–39 y: 21%<br>40–59 y: 55%<br>60+ y: 23% | |
| Shindhe [55] | Karnataka (India) (08/03/2020–21/07/2020) | COVID-19 | Premature mortality | 27,108,524 | 0.010/29,855 | 72,953,823 | 0–39 y: 28%<br>40–59 y: 70%<br>60+ y: 2% | NA |

**Table 3** (continued)

| First author [reference] | Location (period of analysis[a]; dd/mm/yy) | Disease definition | Loss category | Productivity losses (2020 Int$[b]) | Productivity losses: as % /per case (2020 Int$) | Annualised productivity losses (2020 Int$) | Share of total losses (%) | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Age-specific losses | Sex-specific losses |
| Swain [53] | India (2020–2022) | COVID-19 | Premature mortality | 6,958,199,370 | 0.024/13,111 | 2,391,268,516 | 0–39 y: 28%<br>40–59 y: 43%<br>60+ y: 29% | Males: 65%<br>Females: 35% |
| Wang [13] | Canada (01/02/2020–30/04/2022) | COVID-19 | Total | 7,229,422,114 | 0.161 | 3,221,570,459 | 0–39 y: 33%<br>40–59 y: 52%<br>60+ y: 16% | Males: 61%<br>Females: 39% |
| | | | Premature mortality | 2,636,723,763 | 0.059/376,030 | 1,174,975,157 | 0–39 y: 15%<br>40–59 y: 62%<br>60+ y: 23% | Males: 73%<br>Females: 27% |
| | | | Absenteeism | 4,592,698,350 | 0.102/1,604 | 2,046,595,302 | 0–39 y: 43%<br>40–59 y: 45%<br>60+ y: 12% | Males: 54%<br>Females: 46% |
| Hultkrantz [31] | Iceland (until 15/08/2021) | COVID-19 | Absenteeism | 18,941,807 | 0.060/not calculable | 12,545,170 | NA | NA |
| | Norway (until 15/08/2021) | | | 233,057,955 | 0.043/not calculable | 158,366,458 | | |
| | Sweden (until 15/08/2021) | | | 1,628,424,607 | 0.181/not calculable | 1,078,506,555 | | |
| Bednar [60] | Czechia (01/2020–10/2022) | Excess all-cause mortality | Premature mortality | The estimates of losses from these five studies could not be included in the cross-study comparison shown in this table because several parameters required were not reported | | | | |
| Cutler [28] | USA (until 05/05/2022) | Long COVID | Absenteeism | | | | | |
| Galjak [59] | Serbia (2020) | COVID-19 | Premature mortality | | | | | |
| Margaretha [30] | USA, Australia, India, Indonesia, Canada (22/01/2021–21/01/2021); Taiwan (22/01/2021–18/01/2021) | COVID-19 | Absenteeism | | | | | |
| Gandhar [58] | India (NA) | COVID-19 | Premature mortality | | | | | |
| | | | Absenteeism | | | | | |

*NA* not available

[a]The starting date for the period of analysis is not reported in some studies. In such cases, only the end date is reported, e.g. "until 15/08/2021" These cases refer to studies which estimate losses in periods starting at the inception of pandemic; therefore, for the purpose of cross-study estimates made here, we assume the day of the first COVID-19 case in the country to be a starting date of the analysis

[b]International dollars (for details on the estimation procedure and cross-study comparison see Sect. 2.5 in the Methods section)

lockdown costs [33]) was identified for the USA at Int$157.6 billion in a study of long COVID [56] and Int$73.1 billion of premature mortality losses [42]. Other studies reporting high annualised losses were those from Spain [34], the UK [40] and Italy [46]. Again, all three were reported by the same leading author who used methods that yielded high losses also in per-death analysis, as shown in Table 3.

More than half of single-country/region estimates are from a study of productivity losses resulting from premature mortality in 54 African countries [29]. Generally, the indirect costs reported therein are relatively low; for most countries, they are below 0.01% of GDP and reach a maximum of 0.19% in South Africa. Using a similar methodological approach, the same author reported losses of >2% of GDP in Spain [34] and almost 1% in Italy [46] and the UK [40].

For further insight into patterns of productivity losses, we examined average values of losses in groups of countries broken down by loss category (Table 4) as well as age- and sex-specific costs (Tables 5 and 6). We grouped the estimates based on two main loss categories (premature mortality and absenteeism) and whether the countries/regions of interest are high-income (HICs) or middle- and lower-income (LMICs).

Regarding average productivity losses by countries/regions, a clear relationship exists between income level (proxied by World Bank classification) and productivity losses experienced from COVID-19 in countries/regions;

**Table 4** Average productivity losses broken down by countries and loss categories

| | No. single country/ region estimates | Productivity losses | |
|---|---|---|---|
| | | As % of GDP (SD) | In Int$ per 1000 population (SD) |
| *World Bank classification* | | | |
| High-income | 28 | 0.656 (1.953) | 69,454 (79,914) |
| Upper-middle income | 15 | 0.119 (0.123) | 13,663 (28,972) |
| Lower-middle income | 30 | 0.063 (0.111) | 4,993 (16,890) |
| Low-income | 23 | 0.007 (0.008) | 101 (271) |
| *World Health Organization region* | | | |
| Africa | 51 | 0.033 (0.064) | 3150 (15,474) |
| Americas | 6 | 0.301 (0.208) | 115,513 (95,227) |
| Eastern Mediterranean | 8 | 0.072 (0.083) | 22,806 (62,082) |
| Europe | 21 | 0.323 (0.487) | 57,988 (70,998) |
| South-East Asia | 6 | 0.150 (0.219) | 20,646 (35,705) |
| Western Pacific | 4 | 2.628 (5.159) | 113,674 (218,849) |
| *Losses categories* | | | |
| Premature mortality | 91 | 0.118 (0.275) | 21,099 (61,024) |
| Absenteeism | 10 | 0.143 (0.199) | 92,618 (85,866) |
| Quarantine/lockdown/cases | 2 | 5.237 (7.253) | 225,055 (306,686) |

*Int$* International dollars, *GDP* gross domestic product, *SD* standard deviation

**Table 5** Age-specific productivity losses for the studies included in the systematic review

| | Average share of losses in age group in total losses (yr) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | All countries | | | High-income countries | | | Middle- and lower-income countries | | |
| | 0–39 (%) | 40–59 (%) | 60+ (%) | 0–39 (%) | 40–59 (%) | 60+ (%) | 0–39 (%) | 40–59 (%) | 60+ (%) |
| Premature mortality losses | 18 | 42 | 40 | 5 | 29 | 65 | 25 | 49 | 26 |
| Absenteeism losses | 42 | 50 | 9 | 32 | 50 | 18 | 51 | 49 | 0[a] |

In total, 24 studies reported age-specific losses [12, 13, 26, 27, 34–36, 38–44, 46–55]

[a]Only two studies reported age-specific absenteeism losses in 'Middle- and lower-income countries' category but did not analyse the older age category. To normalise age intervals across studies, we assumed an equal distribution of losses across all single ages as defined in particular intervals in source studies (e.g., for an age band 31–45 years reported originally in the study analysed, we assigned 9/15 of the losses to interval 0–39 years and 6/15 to interval 40–59 years). The averages shown are not weighted. Detailed calculations for each study included are shown in Online Resource 3

**Table 6** Sex-specific productivity losses for the studies included in the systematic review

| | Average share of losses in age-group in total losses | | | | | |
|---|---|---|---|---|---|---|
| | All countries | | High-income countries | | Middle- and lower-income countries | |
| | Men (%) | Women (%) | Men (%) | Women (%) | Men (%) | Women (%) |
| Premature mortality losses | 77 | 23 | 77 | 23 | 75 | 25 |
| Absenteeism losses | 72 | 28 | 54 | 46 | 81 | 19 |

Seven studies reported sex-specific losses [11, 13, 36, 38, 39, 45, 53]. The averages shown are not weighted. Detailed calculations for each study included are shown in Online Resource 3

HICs lost 0.656% of GDP on average and this share declined with each income group to 0.007% lost in low-income countries (Table 4). The same pattern is evident for losses expressed in Int$ per 1000 population. The highest average losses for WHO regions were identified in the Western Pacific (2.628% of GDP and Int$113,674 per 1000 population); however, these high losses were due to an outlier effect of a Chinese study accounting for enormous lockdown costs [33]. Substantial average losses of > 0.3% of GDP were identified for studies analysing data from the Americas and Europe, while African losses were the lowest. Considering loss categories, lockdown/quarantine/cases translated to as much as 5.237% of GDP, but again, this results from high losses identified in a study from China in which this category yielded 99.9% of total losses [33]. Interestingly, losses from absenteeism proved to be higher than the cost of premature mortality. Generally, variation in all categories analysed here was substantial with SD values greater than average values in almost all cases. Based on results from 24 studies, we see that the highest losses were identified in the middle-aged (40–59 years) category for all countries combined, both in premature mortality and absenteeism (42% and 50%, respectively) (Table 5). The picture is more nuanced though, once we look separately at the two cost categories distinctly. For mortality in HICs, it was the elderly category that was much more important in terms of overall losses; its share was as much as 65% of total losses. On the other hand, for LMICs countries, the share of losses among the young (0–39 years) was relatively high (25% of the total and 5 times higher share than in HICs) and comparable to the elderly group. For absenteeism loss distribution across age groups, we see that the share of costs attributable to work absence of the young is higher than in mortality; in non-HICs, it is even higher than for the middle-aged.

Considering sex-specific losses, we observed more homogenous shares of costs attributable to males and females across income groups and cost categories (Table 6). Yet, the sex-specific figures are based on results from 7 studies (14 single estimates) only; thus, caution is required here when making across-group comparisons. More than 3/4 of mortality losses resulted from men's deaths and this was homogenous across country groups with a slightly higher share in HICs (77%) than in the remaining countries (75%). The distribution of losses between sexes for absenteeism was quite similar; however, costs due to men's absence were 54% of total losses. As this last share was only available for a single study [13] results need to be treated with caution.

## 4 Discussion

This study aimed to systematically review the evidence on productivity losses due to health burden from the COVID-19 pandemic based on findings from population-level studies. We identified 38 studies meeting inclusion criteria and based on requirements regarding data extracted, 33 of the studies were included in the cross-study quantitative comparison using universal currency and times settings (2020 Int$).

### 4.1 Interpretation of Main Review Findings

Of the 96 unique estimates, most identified economy-level losses of < 0.1% of GDP and used the human capital approach to estimate losses resulting mostly from COVID-19 mortality. Of the studies concerned with health problems associated with COVID-19, the highest productivity losses were identified in Spain in the very initial phase of the pandemic (2.1% of GDP lost until 19 Apr 2020 [34]). On the other hand, no losses were identified in Germany until 15 May 2020 [11] but this finding relies on an excess mortality measure, not COVID-19 deaths as was the case in Spain. Therefore, these two extreme estimates cannot be compared because of a crucial methodological difference. The highest identified productivity losses of > 10% of GDP were reported in the Chinese study [33] concerned with the cost of mortality, cases and lockdowns in the 1st quarter of 2020. Interestingly, 99.9% of the cost in this study resulted from lockdowns, a cost category that is beyond the core scope of this review. The remarkable share of this loss category originates from restrictive non-pharmaceutical interventions (NPIs) in China in the initial phase of the pandemic [61, 62]. This strategy allowed for a slower spread of infection there and low COVID-19 mortality [63, 64]. Only one more study reported losses from lockdown [32]; in Mongolia, the share of losses from this cost category was remarkably high (98%). Yet, in this country, no COVID-19 deaths were reported in the period analysed. Thus, although evidence is scarce, NPIs like lockdowns and social distancing measures might lead to a substantial economic burden of productivity losses. Nonetheless, more research is needed in other settings, particularly when less restrictive NPIs are in place, to verify if lockdowns lead to comparable losses. Ultimately, less stringent policies aimed at mitigating the virus spread would translate to higher mortality and absenteeism losses due to greater death/work absence rates [65, 66]. Such a mechanism might be inferred from a study of absenteeism losses in three Nordic countries [31]; the burden of losses in Sweden, where less restrictive NPIs (e.g., no national lockdowns) were introduced in the first months of the pandemic [67, 68], proved to be 3–4 times higher (in terms of GDP share lost) than the respective losses in Iceland and Norway.

Our cross-country comparison of losses identified a clear income gradient of productivity losses within groups of countries categorised according to the World Bank's classification. High-income countries lost 0.656% of their GDP on average and this share declined with each consecutive group towards 0.007% GDP lost in low-income countries. The explanation behind this pattern appears to result from different demographic structures and socio-economic characteristics of particular country groups. Generally, high-income countries have older populations than other countries. Since COVID-19 affects the elderly more than the young [69, 70], a greater share of the population in rich countries suffers from health deterioration that leads to productivity losses. This effect is strengthened by the higher age of exiting the labour market in high-income countries. Additionally, relatively low losses in less economically developed countries might result from their large informal economies [71]. This is because losses from the informal economy are not identifiable in the productivity losses framework that uses GDP- or income-based approach. Yet, the above reasoning only partially explains the income gradient and it should be noted that some lower-income countries (e.g., India) also experienced a large COVID-19 health burden. In addition, a systematic review [72] claims that infection fatality rates from COVID-19 were roughly 2 times higher in developing countries than in high-income ones.

For age-specific losses, we identified some interesting patterns that reflect differences across groups of countries and loss categories. In all countries combined, mortality losses were similar in the middle-aged group (40–59 years: 42% of total losses) and elderly (60+ years: 40%) categories. However, in high-income countries, the losses from mortality in the elderly accounted for 65% of total losses. This plausibly results from the higher economic activity of those aged 60+ years in developed countries than in the developing countries, as discussed above. Interestingly, the share of mortality losses among the young (aged 0–39 years) in developing countries is five times higher than in high-income countries (25% and 5%) and this perhaps indicates the difference in health system capabilities across the countries [73]. Considering absenteeism losses, these are much more pronounced in the younger population with 42% of total losses in all the countries. This large share is not surprising as the employment rates are high in this group; additionally, the young bore a large burden of childcare absenteeism during school closures in the initial period of the pandemic [74]. Considering sex-specific productivity losses, we note that the cost of COVID-19 in men accounted for around 3/4 of total losses and this might be explained by males having greater vulnerability to the virus [75] as well as their higher employment rates, greater income levels, and longer periods of economic activity before retirement.

## 4.2 Methodological Approaches Identified

One of our aims in this review was to overview the methodological approaches used to estimate productivity losses from the recent coronavirus pandemic. We focused particularly on estimation methods, loss categories, and specific diagnoses analysed.

All studies included in the review that explicitly stated an approach to cost estimation, used HCA, the most commonly used method of indirect cost estimation [76]; consequently, no study used the FCA, neither in a base scenario nor in a sensitivity analysis. Therefore, caution is needed when analysing the results of our review as population-level research utilising the friction cost method is missing. This shortcoming should be kept in mind as the review of the two methods shows that results based on FCA were even 72 times lower than those resulting from the use of HCA [9]. Only one study used the proxy good approach to analyse losses from non-market activities unproduced due to premature mortality [11]. Therefore, the scope of estimation methods used in the studies included is limited and does not allow for a comprehensive assessment of the phenomenon of interest.

Even though all the eligible studies used HCA, it was still infeasible to make truthful comparisons between the estimates. This is because included studies made substantially different assumptions in estimation procedures. For example, in some studies using GDP as a productivity measure [34–36, 38, 40–42, 52], life expectancy was used as an upper bound for identifying a population of interest, while other studies [12, 13, 45, 55, 57] used retirement age (legal or factual). The former approach might overestimate losses if it fails to account for the fact that labour participation and productivity among the elderly decrease with age. On the other hand, retirement age as a population cut-off point undervalues losses because it disregards the fact that some people continue to work once reaching retirement age and most deliver unpaid production within social activities. The above makes cross-study comparisons challenging and requires caution when interpreting findings.

An interesting finding possibly associated with the use of life expectancy as a threshold for choosing a population of interest arises from per-death analysis and annualised loss analysis. The studies using the life expectancy approach, and at the same time those from a team led by the same author, reported virtually the highest costs across all the studies with comparable settings. Therefore, the overrepresentation of findings from a single methodological approach and author team calls for caution when drawing conclusions from this review.

Overall, losses from premature mortality were the most investigated cost category in the studies included in the review. This plausibly results from the fact that COVID-19 was a highly lethal disease from the onset of the pandemic [77, 78] and mortality data were relatively easily available. Unsurprisingly, the cross-study comparison revealed quite substantial differences between the estimates of mortality costs. Spain experienced a loss of 2.1% of GDP due to premature COVID-19 mortality [34] while the same methodological approach shows no losses in some African countries [29] or minor indirect costs in Japan (0.01%) [49] or Germany (0.05%) [43]. The explanation behind these differences results from different death burden across the countries. Japan experienced much lower COVID-19 mortality than most Western European countries or the USA [79, 80]. However, this varying magnitude of losses might result from differences in reporting COVID-19 deaths in particular settings, e.g., divergence in the way deaths are recorded, particularly in cases where COVID-19 is not the direct cause of death, but rather a contributing cause of complications in other diseases [81, 82]. It was also recognised that in some settings governments were unable to sustain standards of COVID-19 death reporting (e.g., in some African countries [83, 84]) and this might bias results downward. In fact, estimates of premature mortality losses from 54 African countries [29] are relatively low compared to those studies that report losses from countries characterised by higher standards of death causes reporting. Moreover, the studies analysed differ in terms of the periods covered. Most of the eligible studies (20 of 33 in the quantitative analysis) refer to 2020, often accounting for only a few months of this year [12, 52, 55]. Such short periods do not identify losses that were yet to come with more dynamic virus spread. An example of this is a zero loss estimate for Germany in the study of excess mortality losses covering the period of 02 Mar–15 May 2020 [11]. With all these limitations, the potential of comparing mortality losses between studies, as we did above, is limited. Therefore, studies using longer time horizons are needed to draw more accurate conclusions on cross-country comparisons of productivity losses.

Absenteeism was another loss category investigated in some studies and resulting losses were substantial in some settings, ranging from 25% of total losses in an Italian study [12] to as much as 88% of the burden in the Indian state of Kerala [39]. Again, these differences might be contextual in terms of the period covered, territory, cost category definition, and between-countries reporting differences, similar to problems explained above in mortality comparisons. Concluding this part of the discussion, it is worth noting that no study provided evidence on presenteeism losses and only limited evidence is available on indirect costs resulting from lockdown and quarantine, possibly due to data constraints.

Considering the definition of health problem (diagnosis), it is clear that studies analysing COVID-19 dominate the picture (33 of 38 eligible studies). Yet, we shall discuss the use of ‘excess’ burden measures in the context of the recent pandemic. Excess mortality used in three reviewed studies [11, 36, 60] is an epidemiological measure often considered a more reliable indicator of the real death burden of a pandemic. Excess mortality approximates the additional number of deaths in a period of interest, compared to the expected number which is usually based on mortality trends or average values observed in near past periods [82, 85]. The main benefit of excess mortality lies in the fact that it not only accounts for fatalities caused directly by SARS-CoV-2 but also for the deaths arising from the pandemic's indirect effects on health systems operation and societies in general [2, 86]. One of the studies analysed here [36], apart from estimating productivity losses from COVID-19 mortality, calculated the losses from overall (all-cause) excess deaths. According to these findings from India, the economic burden from excess mortality was more than ten times greater than losses attributable to COVID-19 deaths. Unfortunately, the excess mortality measure has its drawbacks and there is no established gold standard for estimating it [85, 86]. For example, an important confounding factor that has a notable impact on the outcome is an adjustment for changing population age structure or the length of the pre-pandemic period used for forecasting an expected number of deaths [85, 87]. Yet, it seems that excess mortality might serve as a more trustworthy measure than the number of deaths caused by COVID-19 when evaluating the effects of the pandemic. Epidemiological literature has already recognized this fact [2, 81, 87] and we think that applied research on productivity losses resulting from the pandemic would also benefit from this approach.

### 4.3 Limitations of the Study

Before concluding, we shall acknowledge the limitations of this study. To begin with, there was a large diversity of methodological approaches identified and this calls for caution in comparing the findings across studies. Next, for most of the studies analysed, the period covered in the estimation is limited to the year 2020 and this precludes us from drawing long- or even medium-term conclusions on the pandemic's economic burden. Also, most studies dealt with COVID-19 mortality, and they rarely accounted for excess mortality—a more reliable measure of the true pandemic death toll. Importantly, we were not able to analyse losses broken down by the wave of the pandemic; such an approach was not feasible as there are no comparable data on the duration of particular waves in a large number of countries covered here. Another limitation is that we could only compare quantitative results across studies to a limited extent. Because estimates from eligible studies are based on population-level data, no mean values, variances or sample sizes are obtainable here; therefore, we could not consider meta-analysis in our review. Finally, the review was limited to studies published in either English, Spanish, or Polish language.

## 5 Conclusions

This study aimed to summarise evidence on productivity losses from the COVID-19 pandemic using relatively homogenous settings of population-level studies. Our intent was to compare estimates across studies from different regions in the hope of providing useful and policy-relevant evidence. We found that losses ranged from 0% to 2.1% of GDP (with an outlier loss of > 10% of GDP due to the lockdown in China), but these estimates heavily depended on the loss categories included and the analysed periods. We found the highest losses in high-income countries, for those aged 40–59 years, and that losses among men contributed to around 3/4 of the total indirect cost. Concluding with these findings, we note that the available evidence on the topic is rather limited. This is because eligible studies (1) are concentrated in limited time settings (mostly 2020); (2) in most cases, they do not account for excess health burden (neither mortality nor morbidity); (3) use the human capital approach solely; and (4) hardly account for non-market losses. Therefore, more research is needed to provide a more detailed picture of productivity losses across countries. Such evidence is important from a public policy standpoint to identify the importance of health-related productivity losses as a part of the overall economic burden of COVID-19. Additionally, it might be crucial for future pandemic preparedness, particularly for the evaluation of non-pharmaceutical interventions aimed at limiting virus spread, which work effectively but at the expense of severe economic losses as (limited) evidence from this review suggests.

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**Availability of data and material** The authors confirm that all data generated or analysed during this study are included in this published article or can be replicated with publicly available sources.

**Ethics approval** This study only used publicly available data and no human participants were involved in the study; therefore, ethics approval was not sought.

**Consent to participate, Consent to publication, Code availability** Not applicable.

**Authors' contributions** Błażej Łyszczarz and Paweł Niewiadomski conceptualised and designed the research, collected the data, performed the analyses, interpreted results and wrote the manuscript. Marta Ortega-Ortega participated in designing the study and in the interpretation of the results, collected the data, and critically revised the manuscript. All authors read and approved the final manuscript.

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EDITED BY
Amirhossein Hessami,
Mazandaran University of Medical Sciences, Iran

REVIEWED BY
Anders Björkman,
Karolinska Institutet (KI), Sweden
Reza Eshraghi,
Isfahan University of Medical Sciences, Iran

*CORRESPONDENCE
Paweł Niewiadomski
pawel.niewiadomski@doktorant.umk.pl

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# Beyond death counts: how COVID-19 affected excess mortality and productive life-years lost across 28 European states, 2020–2023

Paweł Niewiadomski[1]*, Jakub Wojtasik[2] and Błażej Łyszczarz[3]

[1]Doctoral School of Medical and Health Sciences, Nicolaus Copernicus University in Toruń, Bydgoszcz, Poland, [2]Statistical Analysis Centre & Doctoral School of Social Sciences, Nicolaus Copernicus University in Toruń, Toruń, Poland, [3]Department of Health Economics, Nicolaus Copernicus University in Toruń, Bydgoszcz, Poland

**Introduction:** Excess mortality attributable to COVID-19 has been extensively investigated in the public health literature. This study extends the scope of previous findings by estimating three interrelated measures, excess deaths, excess Years of Life Lost, and excess Years of Potential Productive Life Lost, in 28 European countries across 2020–2023.

**Materials and methods:** Using annual sex- and 5-year age-specific mortality data for 2002–2019, we applied a multiverse modelling strategy combining all possible baseline windows with four alternative trend specifications. Expected mortality for 2020–2023 was obtained from the best-performing specification, derived using model selection criteria, after trimming outlying forecasts. We define excess mortality burden in terms of three measures: excess deaths, excess Years of Life Lost (eYLL), and excess Years of Potential Productive Life Lost (eYPPLL). Excess mortality was estimated by comparing observed and expected deaths, and was used to obtain eYLL and eYPPLL. Sensitivity analyses included alternative trend assumptions, time-series forecasts, and varying life-expectancy and labour market parameters.

**Results:** We identified a total of 1,540,034 excess deaths, corresponding to 16,695,365 eYLL and 1,997,095 eYPPLL. Central and Eastern Europe bore the heaviest burden of excess deaths, while the Northern countries were the least affected by COVID-19 mortality. We identified a relatively high health burden in the working population, particularly among men and in Central and Eastern Europe. The male excess in productive life-years lost (eYPPLL) was the strongest among all three measures, further highlighting mortality burden in younger-aged men. These results underscore varying labour market vulnerability to the pandemic across European states.

**Conclusion:** Our findings underscore marked geographic and sex differences in excess deaths and life-years lost, with particularly high disparities among the working-age population. These patterns emphasise the need for strengthening health systems' resilience and tailoring post-pandemic recovery efforts to the most affected populations.

KEYWORDS

COVID-19, Europe, excess mortality, excess years of life lost, excess years of potential productive life lost

# 1 Introduction

Excess mortality attributable to the COVID-19 pandemic is one of the most extensively researched topics in the recent epidemiological literature (see systematic reviews) (1, 2). In general, excess mortality is defined as a residual difference between observed and expected (baseline) mortality, the latter representing a situation had the pandemic not occurred (3–8). The concept attracts interest as COVID-19 mortality statistics have proven to be an unreliable measure of the true pandemic death toll (9, 10). This results from the limited capabilities in identifying deaths that were caused directly by the novel coronavirus, usually leading to an underestimation of COVID-19 mortality (11, 12). Despite its conceptual attractiveness and straightforward interpretation, research in excess mortality estimation encounters challenges. Particularly, methodological choices significantly affect findings, leading to substantially different excess mortality estimates across studies. The choices regarding the mortality measure used, methods and reference periods chosen to determine baseline mortality, and data time units applied lead to meaningfully varying estimates (13, 14).

Yet, despite this abundance of excess mortality estimates, there are still under-researched areas. Particularly, apart from the studies concerned with the pandemic years 2020–21 (11, 14, 15), available findings are usually focused on a single country, and limited cross-country evidence is available to compare the mortality burden across states recently. Also, most previous research reported on mortality in all-age populations or wide age groups (e.g., <65 and 65+) (12). Furthermore, most studies assessed general excess mortality measures of death counts, rates or z-scores (12, 15) and did not contextualise this burden to the wider public health and economic context by providing estimates of years of life or productive life lost.

In this study, we aim to contribute to the literature on excess mortality associated with COVID-19 by focusing on the above under-researched areas. Particularly, we estimate the excess mortality burden in terms of three interrelated measures: excess deaths (eD), excess Years of Life Lost (eYLL), and excess Years of Potential Productive Life Lost (eYPPLL). By estimating eYPPLL, we emphasise how the pandemic eroded the working-age population and labour market potential. This economic view is important because European economies were already strained with labour shortages before COVID-19 (16). Additionally, we provide estimates on 28 European countries [all the European Union (EU) member states and Norway] across the period 2020–2023, allowing for cross-country comparisons both during the pandemic and post-pandemic. Also, in contrast to previous evidence based on provisional mortality statistics, e.g., (17), our analysis relies on the final, complete dataset of death counts by Eurostat. Another value added of this research is relying on disaggregated (5-year) age-group-specific data, allowing for a more nuanced picture of the mortality burden. To reduce arbitrariness in baseline selection, instead of choosing a single reference period, we analysed all possible baseline windows across several trend specifications and applied formal model selection criteria to identify the best-performing forecasting model.

Therefore, this study aimed to assess the excess mortality burden in 28 European countries (EU and Norway) in the period 2020–2023 using sex- and detailed age-specific data from Eurostat. The study used annual death counts for 2002–2019 and implemented a multiverse modelling framework across 18 alternative baseline windows and four alternative trend specifications, trimmed forecasting outliers, and identified the best-performing specification using model selection criteria. This final model was then applied consistently to generate expected mortality for 2020–2023. Excess deaths were then weighted by remaining life expectancy (LE) to compute eYLL and country- and sex-specific work periods to compute eYPPLL. By pairing these two life-year indicators with standard excess death counts, the study reveals not only the scale of premature mortality in Europe but also the magnitude of productive life lost, information essential for understanding post-pandemic labour market pressures and for designing policies that balance health resilience with economic sustainability.

# 2 Materials and methods

## 2.1 General approach

This study used annual all-cause mortality and population data from Eurostat (18–20) on 28 European states (27 EU countries and Norway) to estimate the sex- and 5-year age-group-specific excess mortality burden during the pandemic and post-pandemic years, 2020–2023. We define excess mortality burden in terms of three interrelated measures: eD, eYLL, and eYPPLL. Data from the 2002–2019 period were used to build a set of regression models across multiple baseline windows and trend specifications, from which the best-performing specification was selected and subsequently used to predict expected mortality for 2020–2023. By comparing expected mortality with observed mortality during the period 2020–2023, we identified whether excess health burden was present in particular countries, age and sex groups, and years.

## 2.2 Definition and measures of excess mortality burden

We define excess mortality burden as additional negative mortality effects resulting from the COVID-19 pandemic. The appropriate approach for assessing the excess mortality burden involves accounting for both direct and indirect effects of COVID-19. The former category represents deaths caused by SARS-CoV-2 infection, while the latter, deaths related to delayed access to treatment, e.g., in cancer care (21), emergency or routine care (22), or mortality caused by pandemic-borne increased substance use (23) and suicides (24), among others.

We use three measures of excess mortality burden. The first is the number of excess deaths, defined as the difference between the number of observed deaths and the number of deaths expected (based on historical data) in the absence of the pandemic. This indicator provides a more comprehensive view of the pandemic's impact beyond reported COVID-19 deaths (25). The second measure of eYLL is based on Years of Life Lost, a public health metric that quantifies the impact of premature mortality by assigning higher weights to deaths at younger ages. It represents the total number of years individuals would have lived if they had not died prematurely (26, 27). Finally, the third measure of eYPPLL is based on Years of Potential Productive Life Lost, an indicator focusing on the economic and societal consequences of premature mortality in the working-age population (28). eYLL and eYPPLL differ from the usual measures of YLL and YPPLL by using input data of excess mortality, instead of regular mortality data.

For the three measures of excess mortality burden, we estimated counts and age-adjusted rates (European standard population) per 100,000 population in each year, country, and sex.

## 2.3 Data characteristics and sources

Annual data on population and all-cause deaths were retrieved from the Eurostat databases (18, 19). COVID-19 deaths data was also retrieved from Eurostat (cause-specific deaths data) (20). Based on the available data, we analysed 28 European countries, including all EU members and Norway. We used country-level data from the 2002–2023 period, broken down by sex, age, and country. The Eurostat mortality database provides death counts for every single age, but due to the small number of cases at young ages in some (low-populated) countries, we aggregated deaths into 18 5-year age groups (0–4, 5–9,..., 80–84, 85+) (15). Mortality data from 2002 to 2019 served as the pre-pandemic baseline for forecasting expected mortality in 2020–2023, using multiple alternative baseline windows.

For some countries, the Eurostat dataset contained missing data points. However, the data completeness was satisfactory, with average population (mortality) data coverage of 99.40% (99.99%), with the lowest value for Hungary (96.89%). In eight out of nine cases, missing entries referred to the population data, mainly in 2002–2010 and age 85+. We imputed missing data using interpolation or applying a trend of the closest age group for which the data was available (for details, see Supplementary file).

## 2.4 Excess mortality estimation

There is no gold methodological standard for mortality predictions, and the choice of method depends on the frequency of observations (from daily to annual), the number of observations used, the length of a reference period, and the specific interest of the research (29). Previous studies proved that estimates can differ depending on the method and reference period (30).

In this study, we aimed to look at excess mortality in more granular age groups than most previous studies, which used either all-age figures combined (31, 32) or wide age intervals, e.g., <65 and 65+ (12) or 0–19, 20–30, 40–64, 65–79, 80+ (33). Our choice was determined by the fact that, apart from estimating excess deaths, we aimed to assess eYLL and eYPPLL, requiring more detailed age-specific data. Unfortunately, this choice comes at the expense of a more aggregated time dimension of data used. Because the weekly death counts for young age groups in low-populated countries are very low and unstable, we used annual data. This approach restricts the selection of estimation methods, as typical seasonal mortality trends are not discernible in annual data. However, previous studies have shown that the excess mortality estimates using weekly and annual data are generally comparable (32, 34).

Among methods applicable to mortality forecasting, we used Ordinary Least Squares (OLS) regression, consistent with previous studies on excess mortality (32, 34–36), with mortality rates (deaths per 100,000 population) regressed on the time variable (year). We did not include age-structure variables because we estimated age-group-specific models. Excess mortality estimates can be sensitive to both the length of the pre-pandemic baseline and the assumed functional form of the time trend. Therefore, to avoid arbitrariness, we analysed all possible consecutive baseline periods ending in the last pre-pandemic year (2019) and estimated a separate model for each. Additionally, for every sex and age group, this multiverse baseline procedure was applied across four alternative model specifications:

- S1—linear trend with full baseline period 2002–2019;
- S2—linear trend with shorter baseline period 2010–2019;
- S3—linear and quadratic trends with full baseline period 2002–2019;
- S4—linear and quadratic trends with shorter baseline period 2010–2019.

For each specification and baseline window, we forecasted sex- and age-specific mortality rates for 2020–2023. Because predictions from very short windows can be unstable, we applied a Tukey 1.5 × IQR (interquartile range) rule to identify outlying forecasts within each specification and year. Outliers were excluded, and the remaining forecasts were averaged within each specification to obtain expected mortality rates for 2020–2023.

To illustrate, under specification S1, for each country, sex and age-group, we estimated all possible OLS models with baseline windows 2002–2019, 2003–2019, ..., 2018–2019, and 2019-only, predicted annual values for 2020–2023, and averaged them while excluding outliers (>1.5 IQR from median). The same multiverse procedure was used for S2 to S4 specifications.

Across all countries, sexes and age groups, this procedure yielded 4,032 fitted models (28 countries × 2 sexes × 18 age groups × 4 specifications). To select one forecasting specification to apply uniformly across all strata, we evaluated S1–S4 using pre-pandemic goodness-of-fit criteria: Akaike Information Criterion (AIC), Mean Absolute Error (MAE), and Root Mean Squared Error (RMSE). For each of the 4,032 cases we recorded which specification achieved the best value for each metric, and the specification with the highest overall number of wins across all metrics was selected as the final forecasting model. This approach provides a transparent, data-driven basis for model choice and follows principles of multiverse analysis previously applied in cross-country excess mortality research (30).

Expected deaths for 2020–2023 were derived by multiplying expected mortality rates by observed population counts (25) and excess mortality for 2020–2023 was calculated as the difference between the observed and expected values.

95% confidence intervals for each model were computed using the formula:

$$y_{a,c,s,t} = \hat{y}_{a,c,s,t} \pm t_{0.975,\ n-1} \sqrt{\frac{\sum_{i\in\{2002,\ldots,2019\}}\left(y_{a,c,i,s} - \widehat{y_{a,c,i,s}}\right)^2}{n-1}\left(\frac{1}{n} + \frac{(x_0-\bar{x})^2}{\sum_{i\in\{2002,\ldots,2019\}}(x_i-\bar{x})^2}\right)},$$

where $t_{0.975,\ n-1}$ is 97.5% point function of t-Student distribution with n-1 degrees of freedom, $\hat{y}_{c,t,a,s}$ is predicted value for country c, year t, age group a and sex s. Aggregated estimates for all ages or both sexes were obtained by summing age-specific predictions. Confidence intervals for these aggregated estimates were computed using standard OLS-based variance formulas under the assumption of independent age-specific errors.

For aggregated estimates (all countries combined, four regions and/or years), we used a confidence interval estimation method based on weighted mean and standard error as widely implemented in meta-analysis techniques. Namely, each of $k$ countries contributes an estimate of the effect size $E_i, i \in \{1,\ldots,k\}$ accompanied by its variance $\mathrm{Var}(E_i)$. The weight assigned to each country is defined as the inverse of this variance: $w_i = \frac{1}{\mathrm{Var}(E_i)}$. The pooled effect size $E_m$ is then calculated as a weighted average of countries included in the study $E_m = \frac{\sum_{i=1}^{k} w_i E_i}{\sum_{i=1}^{k} w_i}$. The variance of the pooled effect is given by $\mathrm{Var}(E_m) = \frac{1}{\sum_{i=1}^{k} w_i}$, and the corresponding standard error is $\mathrm{SE}(E_m) = \sqrt{\frac{1}{\sum_{i=1}^{k} w_i}}$. To construct a confidence interval around the pooled estimate, one typically uses the normal approximation:

$$\mathrm{CI} = E_m \pm Z_{\alpha/2} \cdot \mathrm{SE}(E_m),$$

where $Z_{\alpha/2}$ is the critical value from the standard normal.

## 2.5 Excess life years lost estimation

As for the eYLL estimation, we relied on our excess deaths estimates and used the pre-pandemic 2019 life expectancy (37). Similarly to the population and mortality data used, LE data were divided into 18 age groups. LE for particular age groups was computed using the arithmetic mean, e.g., for the group of females aged 20–24, the average LE was the mean value of LE of women aged from 20 to 24. Next, we determined the number of eYLL by multiplying the average LE in a specific sex and age group by the excess deaths observed within that group. The following formula was applied:

$$eYLL_{c,s.t} = \sum_a eD_{a,c,s,t} \times LE_{a,c,s}^{2019}$$

where a—5-year age group; c—country; s—sex; t—year (2020–2023); $eD_{a,c,s,t}$—country-, age-group- and sex-specific excess deaths in a year t; $LE_{a,c,s}^{2019}$—country-, age-group- and sex-specific remaining life expectancy in 2019.

To quantify eYPPLL, we first derived sex-specific work-period length for each country ($WP_{c,s}$). This was done by subtracting the sex- and country-specific average age of starting a first regular job ($EntryAge_{c,s}$) (38) from the sex- and country-specific effective age of labour market exit ($ExitAge_{c,s}$) (39).

$$WP_{c,s} = ExitAge_{c,s} - EntryAge_{c,s}$$

$EntryAge_{c,s}$ was derived from the EU Statistics on Income and Living Conditions (EU-SILC) survey conducted among member states' populations (survey item PL190: "When began first regular job"). For $ExitAge_{c,s}$, we used European Commission data on the Cohort Simulation Model's cumulated exit probabilities for the reference age group 51–74 for the year 2023 [Tables II.1.46 & II.1.47 in (39)].

Next, for each country c, sex s, and calendar year t, we calculated eYPPLL assuming that a death at a particular age group occurs at the mid-point age ($MP_{a,c,s}$), e.g., at the age of 32 for the group 30–34, and summed years lost across the working age (aged 20–64) population (age groups <20 are excluded by definition). Therefore, the following formula was applied:

$$eYPPLL_{c,s.t} = \sum_{a=20-64} eD_{a,c,s,t} \times \left(WP_{c,s} - MP_{a,c,s}\right)^+$$

where $(x)^+ = \max(0,x)$ ensures that deaths occurring at or above the retirement age add zero productive years lost.

## 2.6 Sensitivity analysis

We evaluated the robustness of excess mortality estimates to alternative trend specifications (S1-S4; deviations of the final specification from the remaining three) and alternative forecasting approaches. For the latter, we applied two commonly used time-series models, Autoregressive Integrated Moving Average (ARIMA) and exponential smoothing (ETS) (40) and compared their forecasts with those from the final OLS specification.

For ARIMA and ETS, we selected the most appropriate specification based on systematic model searches using AIC. Specifically, for the ARIMA model we evaluated all combinations of ARIMA(p,d,q) with $p$ = 0,1,2, d = 0,1 and q = 0,1,2, and chose the model with the lowest AIC. For the ETS, we considered variants without trend, with additive and multiplicative trend components, and with the damping parameter controlling trend flattening (40). Again, the ETS model with the lowest AIC was chosen.

For eYLL, we examined robustness to alternative life expectancy assumption—projected LE in 2050 (data from the United Nations World Population Prospects 2024) (37) following Martinez et al. (27). For eYPPLL, we examined robustness to alternative definitions of productive lifespan by replacing country- and sex-specific labour-market entry and exit ages with a fixed working life span from ages 20 to 64.

## 2.7 Software

All analyses, data pre-processing and visualisations were carried out in R (v. 4.4.1) using RStudio (v. 2024.09) and Python (3.11.6) with libraries pandas (2.2.3), numpy (2.2.1) and statsmodels (0.14.4).

# 3 Results

## 3.1 Evaluation of baseline trend specifications

To identify the forecasting model to be applied uniformly across all countries, sexes, and age groups, we compared the performance of the four candidate specifications (S1–S4) using three goodness-of-fit metrics (AIC, MAE and RMSE) computed on pre-pandemic data. In total, 4,032 models (28 countries × 2 sexes × 18 age groups × 4 specifications) were evaluated.

Across all comparisons, the short-baseline linear model (S2) achieved the best performance. For AIC, S2 obtained 3,057 wins, followed by S4 (975), while S1 and S3 had no wins. For MAE, S2 achieved 1,332 wins, again outperforming S4 (920), S1 (71) and S3 (55). For RMSE, S2 achieved 1,290 wins, followed by S4 (865), with S3 (36) and S1 (28) far behind. Summed across all three metrics, S2 received 5,679 wins, more than double the next-best specification (S4: 2760 wins). Based on these results, S2 was selected as the final forecasting model. This specification corresponds to a linear trend fitted over the 2010–2019 baseline window multiverse, combined with outlier trimming and averaging as described in Section 2.4. This model, therefore, served as the basis for generating expected mortality for 2020–2023 in all subsequent analyses.

## 3.2 Excess deaths and excess mortality rates

We identified a total of 1,540,034 excess deaths (eD; Table 1) in the 28 European countries across 2020–2023. This burden was unequally distributed over time, with the highest figure estimated for 2021 (562,798 eD), followed by 2020 (451,869), 2022 (421,595), and 2023 (103,771). The highest number of eD across the whole period was identified in Central and Eastern Europe (CEE; 524,399; 34.1% of all). In Southern Europe (SE), we identified 506,309 eD (32.9%), in Western Europe (WE)—425,769 eD (27.6%) and in Northern Europe (NE)—83,557 eD (5.4%). The countries with the highest burden of eD were Italy (266,462; 17.3% of all), Poland (213,041; 13.8%), Germany (164,382; 10.7%), France (156,840; 10.2%) and Spain (136,756; 8.9%). Men accounted for 54.8% (844,449) of all eD, but this share varied across countries, with less than half of male eD in Cyprus (42.7%), Ireland (44.1%), Lithuania (43.7%), Malta (46.2%), and Portugal (41.9%); and >60% in Germany (63.9%), Greece (61.4%), Norway (60.6%) and Sweden (66.2%).

The age-standardised excess mortality rate per 100,000 population (eM_R) across all countries and the whole period was 87 (CI: 84–91); for men, it was 127 (CI: 123–132) and for women, 61 (CI: 58–63). It was 2021 when eM_Rs were the highest (126; CI: 119–133), followed by 2020 (86; CI: 80–91), 2022 (85; CI: 77–93), and 2023 (21; CI: 12–30). For all years, the eM_Rs were higher among men than women (Supplementary Table S1).

CEE experienced the highest excess mortality; for all years combined, eM_R was 190 (CI: 182–198) there, and it was more than double the level of SE states (84; CI: 78–91), and more than triple of rates in WE (58; CI: 52–64) and NE (54; CI: 47–62) countries (Supplementary Table S1). As for the time distribution of eM_R, CEE countries experienced the highest burden in 2020–2022, but in 2023, these countries had negative eM_Rs. For individual countries, the highest four-year eM_R was observed in Bulgaria (257; CI: 239–274), Romania (209; CI: 188–230), and Slovakia (201; CI: 173–229), and the lowest in Denmark (13; CI: −10–37), Luxembourg (24; CI: −3–50), and Norway (26; CI: 7–45). For sex-specific eM_Rs, the country ranking was not much different, with CEE and three Baltic states (Lithuania, Latvia, and Estonia) having the highest eM_Rs, and Northern and Western countries experiencing the lowest values of this measure (Supplementary Table S1).

For particular years, 2021 shows the greatest eM_Rs, with Bulgaria, Slovakia, and Romania exhibiting the highest values in both sexes (Figure 1; detailed data in Supplementary Table S1). However, for some countries, we observed eM_Rs to be higher in 2022 than in 2021, and this was true for Austria, Belgium, Denmark, Finland, France, Germany, Italy, Norway, and Spain, among others. In 2023, some of the countries that were most burdened in previous years had shown reduced (negative excess) mortality, and these were Bulgaria, Lithuania, Hungary and Romania. Additionally, Greece (men), as well as Finland and the Netherlands (both sexes), all of which were mildly affected in previous years, experienced a relatively high excess mortality burden in 2023.

## 3.3 Excess years of life lost

1,540,034 excess deaths translated to a total of 16,695,365 excess years of life lost (eYLL; Table 2). Time distribution of eYLL reflects excess death patterns, with the highest share of eYLL in 2021 (41.0%) and the lowest in 2023 (7.7%). Analogously to eD, the region most burdened in terms of eYLL was CEE, with 5.8 million eYLL (34.6% of total); a large share of the total eYLL in this region resulted from higher excess mortality in younger age groups. For Southern and Western countries, the respective eYLL (% of total) were 5.1 million (30.8%) and 4.8 million (28.5%). The countries with the highest eYLL were Italy (2.7 million; 16.1%), Poland (2.4 million; 14.4% of all), Germany (2.0 million; 12.0%), France (1.6 million; 9.7%), and Spain (1.5 million; 8.9%). Men accounted for 58.0% (9.7 million) of all eYLL, with the highest shares for this measure identified in Sweden (76.8%), Austria (65.7%) and Germany (64.4%).

The age-standardised excess years of life lost per 100,000 population (eYLL_R) for all years and countries combined was 974 (CI: 922–1,026) and was higher in men (1,304; CI: 1,239–1,369) than in women (695; CI: 657–734; Supplementary Table S2). Clearly, time variation in this measure reflects what we observed in excess mortality, with 2021 being the most burdening year (for both sexes combined: eYLL_R = 1,581; CI: 1,482–1,681), and 2023 with the lowest rate of years lost (254; CI: 114–393). For all years, the eYLL_R was higher among men than women (Supplementary Table S2). In 2021, the eYLL_R was as much as 4,405 (CI: 4,176-4,634) in CEE (5,638; CI:

TABLE 1 Excess deaths in 28 European countries in 2020–2023.

| Country | 2020 | | 2021 | | 2022 | | 2023 | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | Males | Females | Males | Females | Males | Females | Males | Females | |
| **CEE** | **82,451 (68,001; 96,902)** | **61,296 (48,621; 73,970)** | **157,689 (140,700; 174,679)** | **139,615 (124,685; 154,546)** | **49,756 (29,885; 69,627)** | **45,769 (27,996; 63,541)** | **−5,999 (−29,473; 17,476)** | **−6,178 (−27,272; 14,915)** | **524,399 (383,143; 665,655)** |
| Bulgaria | 9,744 (9,038; 10,451) | 6,571 (5,322; 7,820) | 21,606 (20,653; 22,559) | 19,632 (18,145; 21,120) | 5,782 (4,562; 7,002) | 4,319 (2,584; 6,053) | −2,953 (−4,447; −1,459) | −3,766 (−5,772; −1,759) | 60,936 (50,085; 71,787) |
| Czechia | 8,710 (6,714; 10,706) | 7,086 (5,518; 8,654) | 16,383 (14,143; 18,623) | 11,322 (9,451; 13,194) | 4,596 (2,038; 7,154) | 3,961 (1,698; 6,225) | 606 (−2,347; 3,558) | −661 (−3,387; 2,064) | 52,003 (33,828; 70,178) |
| Hungary | 4,921 (3,301; 6,541) | 4,999 (3,689; 6,309) | 13,455 (11,435; 15,475) | 11,151 (9,594; 12,708) | 3,498 (1,014; 5,983) | 2,509 (650; 4,368) | −93 (−3,106; 2,920) | −1,331 (−3,495; 834) | 39,109 (23,081; 55,137) |
| Poland | 35,548 (29,864; 41,233) | 26,495 (22,065; 30,925) | 58,024 (51,380; 64,667) | 51,960 (46,600; 57,321) | 20,376 (12,592; 28,160) | 20,578 (13,917; 27,239) | −690 (−9,886; 8,507) | 748 (−7,262; 8,759) | 213,041 (159,269; 266,812) |
| Romania | 20,928 (17,632; 24,223) | 13,851 (10,650; 17,052) | 38,220 (34,393; 42,047) | 36,396 (32,807; 39,985) | 12,219 (7,909; 16,528) | 11,014 (6,995; 15,033) | −3,291 (−8,325; 1,743) | −1,952 (−6,661; 2,757) | 127,384 (95,400; 159,368) |
| Slovakia | 2,600 (1,452; 3,748) | 2,293 (1,377; 3,210) | 10,002 (8,695; 11,308) | 9,154 (8,090; 10,219) | 3,285 (1,770; 4,799) | 3,388 (2,154; 4,623) | 422 (−1,363; 2,207) | 783 (−695; 2,260) | 31,927 (21,480; 42,374) |
| **NE** | **8,245 (656; 15,833)** | **5,702 (724; 10,680)** | **13,274 (4,310; 22,237)** | **13,179 (6,883; 19,474)** | **14,757 (4,077; 25,437)** | **15,265 (7,207; 23,322)** | **7,976 (−4,712; 20,664)** | **5,160 (−4,866; 15,186)** | **83,557 (14,280; 152,834)** |
| Denmark | −61 (−1,183; 1,062) | −312 (−1,324; 701) | 644 (−770; 2,059) | 685 (−536; 1,906) | 1,329 (−447; 3,105) | 1,494 (1; 2,988) | 605 (−1,575; 2,785) | 310 (−1,487; 2,107) | 4,695 (−7,321; 16,711) |
| Estonia | 161 (−205; 527) | 125 (−175; 424) | 1,524 (1,088; 1,960) | 1,551 (1,183; 1,919) | 1,010 (487; 1,533) | 912 (463; 1,360) | 475 (−151; 1,101) | 88 (−455; 632) | 5,846 (2,235; 9,456) |
| Finland | 473 (−613; 1,560) | 240 (−345; 825) | 1,377 (143; 2,612) | 1,041 (325; 1,758) | 3,603 (2,161; 5,045) | 3,756 (2,854; 4,658) | 3,025 (1,354; 4,695) | 2,546 (1,443; 3,650) | 16,063 (7,322; 24,803) |
| Ireland | 172 (−617; 961) | 305 (−288; 897) | 1,076 (168; 1,985) | 897 (204; 1,589) | 896 (−179; 1,971) | 1,422 (580; 2,265) | 828 (−446; 2,103) | 1,138 (102; 2,174) | 6,735 (−475; 13,946) |
| Latvia | 419 (−30; 868) | 542 (113; 972) | 3,269 (2,754; 3,784) | 3,663 (3,122; 4,204) | 1,881 (1,272; 2,491) | 1,679 (1,009; 2,350) | 870 (142; 1,598) | 141 (−681; 964) | 12,466 (7,701; 17,231) |
| Lithuania | 2,889 (1,707; 4,071) | 2,272 (1,576; 2,967) | 3,706 (2,278; 5,133) | 5,102 (4,226; 5,977) | 1,653 (0; 3,306) | 2,941 (1,786; 4,097) | −622 (−2,558; 1,314) | −486 (−1,932; 961) | 17,455 (7,084; 27,826) |
| Sweden | 4,223 (2,694; 5,751) | 2,859 (1,948; 3,771) | 1,330 (−471; 3,131) | −185 (−1,488; 1,118) | 1,916 (−276; 4,109) | 1,239 (−578; 3,055) | 1,418 (−1,248; 4,084) | 634 (−1,750; 3,019) | 13,435 (−1,169; 28,039) |
| Norway | −33 (−1,097; 1,032) | −329 (−781; 123) | 347 (−880; 1,574) | 425 (−153; 1,004) | 2,468 (1,058; 3,877) | 1,821 (1,092; 2,549) | 1,377 (−230; 2,984) | 787 (−105; 1,679) | 6,863 (−1,096; 14,821) |

*(Continued)*

TABLE 1 (Continued)

| Country | 2020 | | 2021 | | 2022 | | 2023 | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | Males | Females | Males | Females | Males | Females | Males | Females | |
| **SE** | **96,568 (75,075; 118,061)** | **91,486 (75,864; 107,107)** | **71,990 (47,240; 96,740)** | **56,516 (37,262; 75,771)** | **69,511 (40,701; 98,321)** | **73,778 (49,778; 97,777)** | **24,851 (−8,770; 58,471)** | **21,610 (−7,553; 50,772)** | **506,309 (309,597; 703,020)** |
| Croatia | 2,448 (1,616; 3,279) | 2,323 (1,625; 3,021) | 5,702 (4,757; 6,648) | 5,361 (4,529; 6,193) | 2,852 (1,745; 3,960) | 3,257 (2,226; 4,288) | 728 (−577; 2,033) | 131 (−1,128; 1,390) | 22,802 (14,793; 30,812) |
| Cyprus | 1 (−153; 154) | 30 (−127; 188) | 351 (106; 595) | 300 (76; 524) | 247 (−92; 586) | 363 (66; 660) | −109 (−553; 334) | −38 (−413; 337) | 1,145 (−1,090; 3,380) |
| Greece | 2,951 (1,076; 4,826) | 2,681 (888; 4,474) | 10,040 (7,709; 12,372) | 7,858 (5,454; 10,262) | 9,304 (6,633; 11,975) | 6,243 (3,234; 9,253) | 3,808 (687; 6,929) | −386 (−4,068; 3,296) | 42,500 (21,614; 63,386) |
| Italy | 51,458 (41,016; 61,900) | 45,470 (39,528; 51,413) | 33,682 (22,094; 45,270) | 27,719 (20,449; 34,989) | 35,883 (22,682; 49,084) | 39,423 (30,501; 48,346) | 16,603 (1,587; 31,619) | 16,224 (5,554; 26,894) | 266,462 (183,410; 349,514) |
| Malta | 166 (58; 274) | 97 (−2; 196) | 93 (−64; 251) | 178 (45; 310) | 141 (−72; 354) | 123 (−40; 286) | 24 (−252; 299) | 95 (−113; 303) | 917 (−439; 2,272) |
| Portugal | 4,046 (2,113; 5,980) | 5,151 (3,428; 6,873) | 4,659 (2,422; 6,896) | 4,937 (2,948; 6,926) | 3,019 (391; 5,647) | 5,179 (2,872; 7,485) | 311 (−2,798; 3,421) | 1,415 (−1,224; 4,055) | 28,717 (10,151; 47,284) |
| Slovenia | 1,385 (935; 1,834) | 1,708 (1,416; 1,999) | 1,387 (822; 1,952) | 896 (521; 1,272) | 616 (−74; 1,307) | 757 (291; 1,224) | 313 (−521; 1,148) | −54 (−635; 527) | 7,009 (2,755; 11,263) |
| Spain | 34,113 (28,413; 39,814) | 34,025 (29,107; 38,943) | 16,075 (9,394; 22,757) | 9,267 (3,240; 15,295) | 17,449 (9,489; 25,408) | 18,432 (10,629; 26,235) | 3,173 (−6,342; 12,688) | 4,222 (−5,526; 13,970) | 136,756 (78,404; 195,108) |
| **WE** | **61,780 (35,981; 87,578)** | **44,343 (26,375; 62,310)** | **72,774 (43,562; 101,985)** | **37,762 (14,905; 60,619)** | **82,357 (48,485; 116,230)** | **70,404 (41,880; 98,928)** | **36,470 (−2,758; 75,699)** | **19,880 (−14,662; 54,422)** | **425,769 (193,768; 657,770)** |
| Austria | 3,821 (2,471; 5,171) | 2,994 (2,079; 3,909) | 4,150 (2,560; 5,741) | 2,543 (1,265; 3,821) | 4,227 (2,326; 6,128) | 3,324 (1,786; 4,862) | 2,586 (345; 4,827) | 1,024 (−793; 2,841) | 24,670 (12,040; 37,301) |
| Belgium | 8,402 (6,180; 10,625) | 8,614 (7,282; 9,946) | 3,637 (1,244; 6,030) | 379 (−1,119; 1,876) | 3,867 (1,202; 6,533) | 4,226 (2,475; 5,976) | 1,623 (−1,379; 4,626) | 1,576 (−473; 3,625) | 32,324 (15,411; 49,237) |
| France | 26,884 (18,911; 34,857) | 21,531 (17,878; 25,184) | 25,681 (16,928; 34,433) | 15,852 (11,248; 20,457) | 27,048 (17,195; 36,900) | 25,100 (19,444; 30,755) | 8,156 (−3,014; 19,326) | 6,588 (−178; 13,354) | 156,840 (98,413; 215,267) |
| Germany | 14,442 (2,896; 25,989) | 6,263 (−4,172; 16,698) | 30,269 (16,907; 43,630) | 13,645 (422; 26,868) | 41,159 (25,430; 56,889) | 32,439 (15,972; 48,906) | 19,121 (699; 37,544) | 7,043 (−13,001; 27,087) | 164,382 (45,154; 283,611) |
| Luxembourg | 128 (15; 242) | 88 (12; 164) | 13 (−165; 191) | 32 (−83; 147) | −82 (−332; 169) | 14 (−144; 172) | −213 (−542; 117) | 23 (−181; 228) | 4 (−1,422; 1,430) |
| Netherlands | 8,101 (5,509; 10,694) | 4,853 (3,296; 6,410) | 9,024 (6,088; 11,960) | 5,310 (3,172; 7,449) | 6,138 (2,664; 9,612) | 5,301 (2,347; 8,256) | 5,196 (1,133; 9,258) | 3,625 (−36; 7,286) | 47,548 (24,172; 70,924) |
| **Total** | **249,043 (179,713; 318,374)** | **202,826 (151,584; 254,068)** | **315,726 (235,811; 395,642)** | **247,072 (183,735; 310,409)** | **216,381 (123,148; 309,614)** | **205,214 (126,861; 283,568)** | **63,299 (−45,712; 172,310)** | **40,472 (−54,352; 135,295)** | **1,540,034 (900,788; 2,179,279)** |

Each cell contains a point estimate and a 95% confidence interval in brackets. CEE, Central and Eastern Europe; NE, Northern Europe; SE, Southern Europe; WE, Western Europe. Bold font represents total values for countries within each of four European regions.

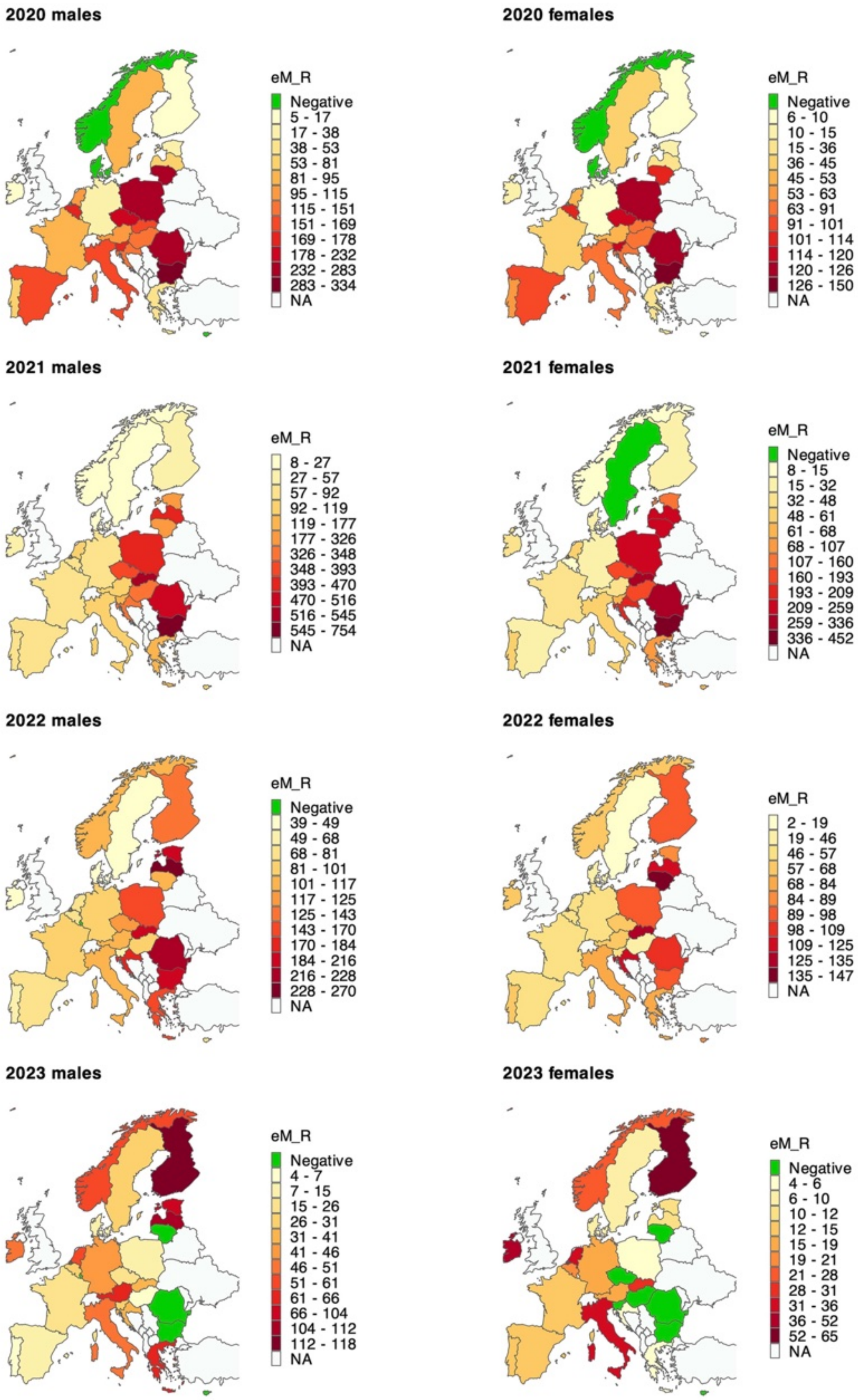


FIGURE 1
Age-standardised excess mortality rate per 100,000 population in 28 countries in 2020–2023. Detailed results with confidence intervals are available in Supplementary Table S1. EM_R—age-standardised excess mortality rate per 100,000 population. Each map uses its own colour scale because the magnitude of excess mortality varies substantially across years (e.g., 2021 shows much higher values than 2023) and sexes.

TABLE 2 Excess years of life lost (eYLL) in 28 European countries in 2020–2023.

| Country | 2020 | | 2021 | | 2022 | | 2023 | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | Males | Females | Males | Females | Males | Females | Males | Females | |
| **CEE** | **911,235 (673,217; 1,149,253)** | **641,146 (476,576; 805,717)** | **1,941,524 (1,660,305; 2,222,744)** | **1,642,874 (1,446,125; 1,839,622)** | **516,908 (185,616; 848,200)** | **390,851 (154,067; 627,636)** | **−154,047 (−543,296; 235,202)** | **−115,478 (−395,276; 164,319)** | **5,775,013 (3,657,334; 7,892,692)** |
| Bulgaria | 107,311 (95,426; 119,195) | 79,594 (65,220; 93,968) | 244,134 (228,161; 260,107) | 233,996 (215,537; 252,456) | 51,099 (30,560; 71,637) | 49,788 (27,364; 72,213) | −31,066 (−56,456; −5,676) | −30,083 (−56,767; −3,399) | 704,773 (549,045; 860,500) |
| Czechia | 81,400 (51,022; 111,778) | 56,619 (35,187; 78,051) | 196,392 (161,628; 231,156) | 132,134 (106,605; 157,664) | 48,871 (8,329; 89,413) | 34,772 (3,883; 65,662) | 4,031 (−43,315; 51,376) | −12,580 (−49,924; 24,764) | 541,638 (273,413; 809,863) |
| Hungary | 56,445 (24,131; 88,759) | 55,624 (35,093; 76,156) | 189,094 (150,156; 228,032) | 159,940 (136,022; 183,858) | 46,773 (364; 93,182) | 38,376 (10,003; 66,750) | −3,706 (−58,603; 51,192) | −930 (−33,930; 32,069) | 541,616 (263,235; 819,998) |
| Poland | 417,993 (321,630; 514,357) | 268,902 (208,164; 329,640) | 744,081 (632,683; 855,479) | 591,318 (518,570; 664,066) | 248,994 (119,423; 378,564) | 191,660 (102,892; 280,428) | −38,984 (−190,534; 112,567) | −12,256 (−117,029; 92,517) | 2,411,708 (1,595,799; 3,227,617) |
| Romania | 221,244 (171,853; 270,634) | 158,240 (122,330; 194,151) | 433,656 (374,087; 493,225) | 415,851 (373,918; 457,784) | 81,202 (11,076; 151,328) | 51,434 (2,232; 100,637) | −88,103 (−169,975; −6,231) | −61,036 (−118,368; −3,704) | 1,212,488 (767,152; 1,657,824) |
| Slovakia | 26,842 (9,155; 44,530) | 22,166 (10,582; 33,751) | 134,168 (113,591; 154,745) | 109,635 (95,475; 123,795) | 39,970 (15,864; 64,076) | 24,820 (7,694; 41,947) | 3,781 (−24,413; 31,975) | 1,407 (−19,257; 22,072) | 362,790 (208,690; 516,890) |
| **NE** | **101,589 (−24,852; 228,030)** | **49,915 (−28,957; 128,787)** | **184,058 (35,192; 332,925)** | **145,073 (45,325; 244,820)** | **187,427 (11,208; 363,646)** | **149,418 (23,193; 275,643)** | **130,408 (−77,814; 338,631)** | **66,456 (−89,708; 222,619)** | **1,014,344 (−106,412; 2,135,100)** |
| Denmark | −2,009 (−19,818; 15,801) | −437 (−15,933; 15,060) | 2,675 (−19,252; 24,602) | 10,311 (−8,453; 29,075) | 12,192 (−14,495; 38,880) | 18,828 (−4,127; 41,784) | 7,503 (−24,404; 39,409) | 6,987 (−20,630; 34,605) | 56,052 (−127,113; 239,217) |
| Estonia | 3,308 (−3,781; 10,398) | 1,324 (−3,374; 6,023) | 20,332 (12,080; 28,583) | 15,517 (9,333; 21,701) | 15,439 (5,683; 25,196) | 8,138 (259; 16,016) | 9,711 (−1,864; 21,287) | 2,393 (−7,487; 12,272) | 76,163 (10,848; 141,477) |
| Finland | 12,366 (−5,997; 30,729) | 353 (−8,599; 9,305) | 15,502 (−6,086; 37,089) | 8,010 (−3,330; 19,350) | 36,350 (10,855; 61,846) | 32,626 (18,152; 47,100) | 32,568 (2,711; 62,425) | 23,156 (5,292; 41,019) | 160,931 (12,999; 308,863) |
| Ireland | 5,133 (−7,781; 18,048) | 6,262 (−2,822; 15,346) | 18,550 (3,467; 33,633) | 13,513 (1,789; 25,236) | 15,363 (−2,644; 33,369) | 17,475 (2,506; 32,445) | 12,257 (−9,429; 33,944) | 11,221 (−7,891; 30,333) | 99,775 (−22,805; 222,355) |
| Latvia | 3,520 (−4,386; 11,427) | 2,707 (−3,673; 9,087) | 44,265 (34,742; 53,789) | 37,437 (29,000; 45,874) | 29,279 (17,595; 40,962) | 15,545 (4,852; 26,239) | 17,623 (3,376; 31,871) | 1,096 (−12,162; 14,354) | 151,472 (69,342; 233,603) |
| Lithuania | 39,761 (17,494; 62,028) | 25,161 (13,916; 36,406) | 59,660 (34,367; 84,952) | 57,689 (44,234; 71,144) | 30,956 (2,200; 59,711) | 31,637 (15,059; 48,215) | 10,053 (−23,220; 43,327) | 1,465 (−18,508; 21,438) | 256,382 (85,542; 427,221) |
| Sweden | 40,278 (16,983; 63,574) | 17,018 (2,798; 31,239) | 21,827 (−5,399; 49,052) | −604 (−19,452; 18,245) | 22,912 (−9,477; 55,301) | 8,245 (−16,729; 33,220) | 20,431 (−18,090; 58,951) | 7,254 (−24,515; 39,023) | 137,362 (−73,881; 348,605) |
| Norway | −770 (−17,565; 16,025) | −2,474 (−11,269; 6,321) | 1,248 (−18,728; 21,224) | 3,200 (−7,796; 14,195) | 24,936 (1,491; 48,380) | 16,923 (3,221; 30,624) | 20,261 (−6,893; 47,415) | 12,884 (−3,807; 29,575) | 76,207 (−61,345; 213,759) |

*(Continued)*

TABLE 2 (Continued)

| Country | 2020 | | 2021 | | 2022 | | 2023 | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | Males | Females | Males | Females | Males | Females | Males | Females | |
| **SE** | **967,482 (664,766; 1,270,198)** | **756,703 (562,021; 951,385)** | **884,969 (538,897; 1,231,041)** | **632,882 (399,884; 865,881)** | **702,554 (302,974; 1,102,134)** | **636,074 (355,762; 916,386)** | **311,372 (−151,167; 773,912)** | **250,435 (−85,075; 585,945)** | **5,142,471 (2,588,062; 7,696,881)** |
| Croatia | 21,100 (10,029; 32,171) | 21,180 (12,583; 29,777) | 55,928 (42,574; 69,283) | 54,019 (43,212; 64,826) | 23,233 (6,771; 39,695) | 23,344 (9,674; 37,014) | 6,064 (−13,797; 25,925) | 776 (−15,992; 17,545) | 205,645 (95,055; 316,235) |
| Cyprus | 364 (−2,201; 2,929) | 788 (−1,465; 3,041) | 5,073 (1,037; 9,109) | 5,196 (1,905; 8,487) | 1,884 (−3,713; 7,481) | 3,697 (−786; 8,180) | −114 (−7,393; 7,165) | −268 (−5,955; 5,418) | 16,620 (−18,570; 51,811) |
| Greece | 26,309 (4,722; 47,896) | 27,684 (7,822; 47,546) | 119,995 (91,819; 148,170) | 93,279 (67,509; 119,050) | 63,227 (29,330; 97,124) | 61,685 (30,335; 93,034) | 7,967 (−32,409; 48,343) | 10,905 (−27,088; 48,898) | 411,050 (172,040; 650,061) |
| Italy | 515,535 (379,669; 651,401) | 359,428 (285,229; 433,627) | 418,210 (269,636; 566,783) | 299,649 (212,296; 387,003) | 363,239 (195,867; 530,611) | 322,070 (217,464; 426,675) | 227,001 (38,442; 415,560) | 178,243 (54,770; 301,717) | 2,683,375 (1,653,373; 3,713,378) |
| Malta | 2,381 (377; 4,385) | −361 (−2,267; 1,545) | 1,638 (−1,439; 4,715) | 848 (−2,081; 3,778) | 2,744 (−1,377; 6,865) | −506 (−4,010; 2,997) | −67 (−5,802; 5,668) | −1,742 (−6,855; 3,371) | 4,936 (−23,455; 33,326) |
| Portugal | 45,358 (16,896; 73,821) | 40,190 (18,005; 62,375) | 52,703 (19,189; 86,216) | 42,828 (16,141; 69,515) | 34,734 (−4,836; 74,303) | 37,808 (5,968; 69,648) | 10,037 (−36,716; 56,790) | 6,029 (−31,420; 43,479) | 269,687 (3,227; 536,148) |
| Slovenia | 11,165 (3,888; 18,443) | 11,293 (6,954; 15,631) | 16,272 (7,086; 25,457) | 9,330 (3,594; 15,066) | 7,053 (−4,088; 18,194) | 6,917 (−223; 14,058) | 3,226 (−10,072; 16,524) | −1,135 (−10,182; 7,912) | 64,121 (−3,044; 131,286) |
| Spain | 345,268 (251,386; 439,151) | 296,502 (235,160; 357,844) | 215,150 (108,994; 321,306) | 127,732 (57,309; 198,155) | 206,441 (85,019; 327,862) | 181,059 (97,340; 264,779) | 57,258 (−83,420; 197,935) | 57,627 (−42,352; 157,605) | 1,487,037 (709,437; 2,264,637) |
| **WE** | **580,079 (184,957; 975,200)** | **313,954 (75,270; 552,638)** | **940,423 (492,082; 1,388,763)** | **465,206 (171,042; 759,371)** | **962,596 (445,058; 1,480,133)** | **699,725 (339,770; 1,059,681)** | **515,623 (−81,551; 1,112,798)** | **285,931 (−147,082; 718,943)** | **4,763,537 (1,479,546; 8,047,527)** |
| Austria | 36,171 (12,565; 59,776) | 22,629 (8,679; 36,580) | 57,023 (29,032; 85,015) | 27,788 (9,490; 46,086) | 48,392 (15,001; 81,784) | 30,443 (7,759; 53,127) | 34,240 (−5,309; 73,789) | 11,121 (−16,467; 38,709) | 267,808 (60,750; 474,866) |
| Belgium | 79,530 (44,047; 115,014) | 62,703 (43,498; 81,907) | 52,332 (13,337; 91,326) | 15,527 (−6,915; 37,969) | 46,549 (2,845; 90,253) | 37,198 (10,680; 63,716) | 18,983 (−30,218; 68,184) | 12,634 (−18,581; 43,849) | 325,456 (58,693; 592,219) |
| France | 244,891 (108,131; 381,651) | 158,912 (102,682; 215,143) | 311,061 (157,729; 464,394) | 163,019 (91,894; 234,145) | 317,805 (143,383; 492,227) | 232,973 (145,313; 320,633) | 120,225 (−77,950; 318,400) | 65,269 (−39,838; 170,377) | 1,614,157 (631,344; 2,596,970) |
| Germany | 136,447 (−23,263; 296,156) | 28,755 (−96,342; 153,852) | 414,719 (232,389; 597,049) | 190,361 (39,031; 341,691) | 471,077 (259,526; 682,628) | 340,249 (156,994; 523,504) | 272,903 (26,900; 518,905) | 155,998 (−64,131; 376,127) | 2,010,509 (531,105; 3,489,913) |
| Luxembourg | 383 (−1,939; 2,705) | 734 (−880; 2,348) | −1,117 (−4,888; 2,654) | 568 (−1,977; 3,113) | −1,260 (−6,496; 3,976) | −661 (−4,271; 2,949) | −4,158 (−11,016; 2,701) | 215 (−4,512; 4,942) | −5,296 (−35,979; 25,388) |
| Netherlands | 82,657 (45,416; 119,898) | 40,220 (17,633; 62,807) | 106,404 (64,483; 148,325) | 67,943 (39,519; 96,367) | 80,033 (30,799; 129,267) | 59,522 (23,293; 95,751) | 73,430 (16,042; 130,818) | 40,694 (−3,553; 84,940) | 550,903 (233,633; 868,173) |

*(Continued)*

TABLE 2 (Continued)

| Country | 2020 | | 2021 | | 2022 | | 2023 | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | Males | Females | Males | Females | Males | Females | Males | Females | |
| **Total** | **2,560,384 (1,498,088; 3,622,680)** | **1,761,718 (1,084,910; 2,438,526)** | **3,950,974 (2,726,476; 5,175,472)** | **2,886,035 (2,062,376; 3,709,694)** | **2,369,484 (944,856; 3,794,113)** | **1,876,068 (872,791; 2,879,345)** | **803,357 (−853,828; 2,460,542)** | **487,343 (−717,140; 1,691,827)** | **16,695,365 (7,618,529; 25,772,200)** |

Each cell contains a point estimate and a 95% confidence interval in brackets. CEE, Central and Eastern Europe; NE, Northern Europe; SE, Southern Europe; WE, Western Europe. Bold font represents total values for countries within each of four European regions.

5,362–5,913 in men and 3,456; CI: 3,279–3,634 in women) and only 782 (CI: 549–1,015) in NE. In 2023, the measure was negative in CEE (Supplementary Table S2).

For individual countries, the highest four-year eYLL_R was observed in Bulgaria (2,930; CI: 2,672–3,188), Lithuania (2,394; CI: 1,699–3,089) and Slovakia (2,055; CI: 1,695–2,414), and the lowest in Luxembourg (56; CI: −447–558), Denmark (168; CI: −192-527), and Norway (255; CI: −58–568). For sex-specific eYLL_Rs, Bulgaria experienced the highest four-year burden in both men (3,720; CI: 3,456-3,983) and women (2,366; CI: 2,125–2,607). Most of the highest year-specific eYLL_Rs were observed in 2021 and all of these referred to CEE or three Baltic states (Latvia, Lithuania, Estonia); yet, these countries contributed with the highest eYLL_Rs also in other years, e.g., Bulgaria, Lithuania, Poland and Romania in 2020; and Estonia, Lithuania, Latvia and Slovakia in 2022 (Figure 2; Supplementary Table S2). Most of these countries had lower or even negative rates of years lost in 2023, but Estonia and Latvia remained the ones with the high burden also in the last year. Interestingly, for women in Sweden, eYLL_R was higher in 2023 than in 2022, exhibiting a delayed effect of the pandemic on years of life lost. In contrast, for the last year analysed, we note significantly decreased eYLL_R compared to a hypothetical non-pandemic scenario in Bulgaria and Romania (both sexes), Malta and Czechia (women), and Luxembourg (men).

## 3.4 Excess years of potential productive life lost

Among the working-age Europeans (20–64 years old), excess mortality resulted in 1,997,095 eYPPLL (Table 3), 12.0% of total eYLL, highlighting the predominant impact of the pandemic on mortality among those aged 65+. As for the time distribution of eYPPLL, we observe a higher share of the burden in 2023 (10.8% of total) than in eYLL (7.7%) and excess deaths (6.7%). Therefore, for the last year analysed, we identified relatively more deaths among the working-age Europeans. As much as 41.0% of the total eYPPLL were identified in CEE, highlighting high mortality in the young-aged, while this share was 27.6% in WE and 22.7% in SE. The countries experiencing the highest eYPPLL were Poland (376,571 years lost; 18.9% of total), Germany (285,718; 14.3%), Italy (193,036; 9.7%), Spain (163,827; 8.2%), and France (144,116; 7.2%). Males accounted for 75.6% of total eYPPLL (1,509,928 years lost) in all countries combined, with the highest shares identified in Portugal (97.3%) and Estonia (90.8%). For several countries (e.g., Finland, Sweden, Austria), we identified negative eYPPLL among females in all years combined; therefore, the respective males' share of >100% cannot be interpreted analogously to countries experiencing positive values for both sexes.

The age-standardised excess years of potential productive life lost per 100,000 population (eYPPLL_R) for all years and countries combined was 181 (CI: 166–197) and was more than double in men (252; CI: 231–273) than in women (102; CI: 93–112; Supplementary Table S3). The measure of productive life lost was the highest in 2021 (324; CI: 294–354, both sexes combined), reflecting this year's greatest mortality surge. Similarly to excess deaths and eYLL_R measures, eYPPLL_R was the lowest in 2023 (82; CI: 39–126), less than half its highest value in 2021.

For regional comparison of productive life lost, we note that CEE countries had the highest values of eYPPLL_R in 2020–2022 (Figure 3; Supplementary Table S3), and this was similar to the other two measures discussed above. However, in 2023, this region was the least burdened, with reduced, but non-significant, rates of excess productive years lost. For particular countries, the highest four-year eYPPLL_R was observed in Lithuania (956; CI: 566–1,347), Bulgaria (783; CI: 704–863), and Latvia (610; CI: 382–839), and the lowest in Luxembourg (−34; CI: −176–108), Sweden (7; CI: −62–77), and Norway (54; CI: −48–155).

For sex-specific eYPPLL_Rs, the four-year rate of excess productive years lost was the highest in Lithuania, both among men (1,427; CI: 794–2,059) and women (513; CI: 356–669). The burden of productive life lost in excess was skewed towards CEE and three Baltic states (Estonia, Latvia, and Lithuania), even more than in the other two measures.

## 3.5 Age-specific excess mortality burden

An age gradient was evident across all three excess mortality measures, with excess mortality identified primarily in age groups >60 years (the results in this sub-section refer to all countries combined). This trend was universal in eD for all 5-year age groups above 60 and both sexes in 2020–2022 (Supplementary Table S4). In 2023, the trend continued with some exceptions; for both sexes aged 60–64, we identified negative eD. Additionally, a reduced mortality was identified in the youngest age groups (0–4, 5–9, and 10–14), mainly in the first pandemic year. In all age groups but the eldest (85+), men account for a majority of eD. In all countries combined, 31.8% of eD were among those aged 85+, with a notable variation between sexes (24.8% in males and 40.4% in females). On the other hand, 12.2% of eD were identified in those below 65 years; this share was 16.4% for men and 7.1% for women (Supplementary Table S5).

For eYLL, the age groups with the most years lost were 65–69 and 75–79, not 85 + as in excess deaths. Again, years lost due to male mortality dominated, apart from those aged >80, where eYLL was higher in women (Supplementary Table S6). Across all countries,

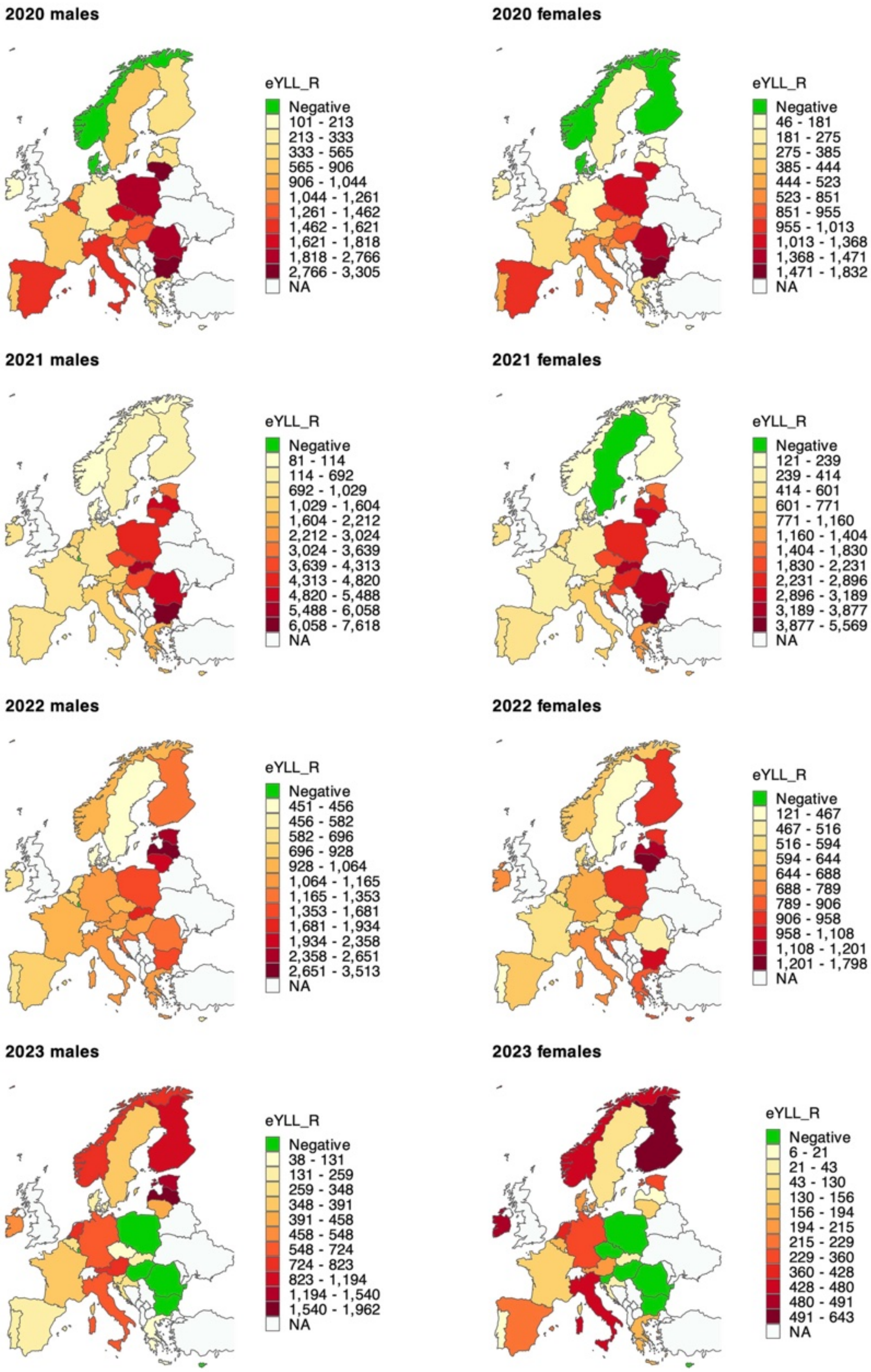


FIGURE 2
Age-standardised excess years of life lost per 100,000 population in 28 countries in 2020–2023. Detailed results with confidence intervals are available in Supplementary Table S2. eYLL_R—age-standardised excess years of life lost rate per 100,000 population. Each map uses its own colour scale because the magnitude of excess years of life lost varies substantially across years (e.g., 2021 shows much higher values than 2023) and sexes.

TABLE 3 Excess years of potential productive life lost (eYPPLL) in 28 European countries in 2020–2023.

| Country | 2020 | | 2021 | | 2022 | | 2023 | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | Males | Females | Males | Females | Males | Females | Males | Females | |
| **CEE** | **139,044 (74,327; 203,760)** | **49,468 (29,442; 69,493)** | **363,232 (286,328; 440,136)** | **149,174 (124,120; 174,228)** | **104,687 (14,540; 194,835)** | **37,606 (6,710; 68,501)** | **−22,484 (−128,235; 83,267)** | **−2,439 (−39,590; 34,712)** | **818,288 (367,643; 1,268,933)** |
| Bulgaria | 19,225 (16,460; 21,991) | 7,307 (6,128; 8,485) | 46,234 (42,135; 50,333) | 23,089 (21,126; 25,051) | 3,272 (−2,249; 8,793) | 3,936 (1,204; 6,668) | −9,020 (−16,070; −1,971) | −3,469 (−7,012; 74) | 90,573 (61,722; 119,423) |
| Czechia | 5,581 (89; 11,073) | 3,034 (1,083; 4,985) | 23,463 (16,997; 29,929) | 10,432 (7,874; 12,990) | 10,949 (3,074; 18,824) | 2,627 (−628; 5,881) | 7,089 (−2,352; 16,530) | −1,312 (−5,441; 2,817) | 61,863 (20,697; 103,028) |
| Hungary | 9,519 (−2,977; 22,016) | 5,084 (477; 9,690) | 45,057 (30,591; 59,523) | 22,063 (16,687; 27,439) | 12,473 (−3,934; 28,880) | 5,110 (−1,169; 11,388) | 2,063 (−16,494; 20,621) | 3,372 (−3,913; 10,657) | 104,742 (19,268; 190,215) |
| Poland | 73,614 (44,743; 102,485) | 18,679 (12,042; 25,315) | 150,640 (118,119; 183,161) | 45,915 (38,140; 53,690) | 62,226 (25,321; 99,130) | 22,870 (13,691; 32,049) | −4,435 (−47,157; 38,286) | 7,063 (−3,612; 17,739) | 376,571 (201,288; 551,855) |
| Romania | 29,662 (18,505; 40,820) | 15,382 (11,086; 19,677) | 75,571 (60,939; 90,202) | 40,303 (34,805; 45,801) | 7,889 (−9,922; 25,699) | 2,745 (−4,227; 9,718) | −20,839 (−42,203; 525) | −7,490 (−15,910; 929) | 143,222 (53,072; 233,371) |
| Slovakia | 1,442 (−2,493; 5,376) | −17 (−1,374; 1,340) | 22,267 (17,547; 26,987) | 7,374 (5,489; 9,258) | 7,879 (2,249; 13,509) | 318 (−2,161; 2,797) | 2,658 (−3,959; 9,276) | −603 (−3,702; 2,496) | 41,318 (11,596; 71,040) |
| **NE** | **20,678 (−11,376; 52,731)** | **2,593 (−10,637; 15,824)** | **41,306 (3,336; 79,275)** | **14,555 (−2,985; 32,096)** | **40,438 (−4,677; 85,553)** | **9,841 (−12,683; 32,365)** | **37,204 (−16,344; 90,752)** | **6,005 (−22,195; 34,206)** | **172,620 (−77,561; 422,802)** |
| Denmark | 1,023 (−3,072; 5,117) | 654 (−1,797; 3,105) | −87 (−4,881; 4,707) | 1,223 (−1,895; 4,341) | 3,328 (−2,355; 9,012) | 1,006 (−2,900; 4,913) | 2,558 (−4,103; 9,219) | 759 (−4,044; 5,562) | 10,464 (−25,048; 45,976) |
| Estonia | 2,064 (−748; 4,877) | −215 (−926; 495) | 4,948 (1,803; 8,093) | 1,039 (−8; 2,086) | 6,076 (2,459; 9,692) | 644 (−748; 2,037) | 5,777 (1,578; 9,976) | 442 (−1,375; 2,260) | 20,775 (2,034; 39,516) |
| Finland | 4,060 (255; 7,865) | −626 (−1,843; 591) | 129 (−4,729; 4,987) | −689 (−2,358; 981) | 2,402 (−3,541; 8,345) | 655 (−1,556; 2,867) | 3,659 (−3,490; 10,808) | −200 (−2,997; 2,596) | 9,390 (−20,260; 39,039) |
| Ireland | 2,740 (−129; 5,609) | 753 (−664; 2,171) | 4,560 (1,278; 7,843) | 1,311 (−896; 3,517) | 3,031 (−838; 6,899) | 1,299 (−1,780; 4,378) | 3,985 (−600; 8,571) | −57 (−4,184; 4,071) | 17,623 (−7,814; 43,059) |
| Latvia | −380 (−2,984; 2,224) | −545 (−1,551; 461) | 13,296 (9,851; 16,741) | 4,040 (2,587; 5,493) | 11,564 (7,095; 16,034) | 1,758 (−167; 3,683) | 8,584 (2,947; 14,222) | −490 (−2,936; 1,955) | 37,827 (14,842; 60,812) |
| Lithuania | 10,784 (1,703; 19,865) | 2,936 (675; 5,197) | 18,134 (8,213; 28,056) | 7,673 (5,093; 10,253) | 9,504 (−1,521; 20,529) | 5,237 (2,232; 8,242) | 6,556 (−6,026; 19,137) | 2,374 (−1,144; 5,891) | 63,197 (9,224; 117,171) |
| Sweden | 381 (−3,315; 4,078) | −968 (−3,336; 1,401) | 1,842 (−2,834; 6,518) | −357 (−3,456; 2,742) | 1,797 (−4,053; 7,648) | −2,675 (−6,604; 1,255) | 1,936 (−5,280; 9,151) | 276 (−4,551; 5,104) | 2,233 (−33,430; 37,896) |
| Norway | 6 (−3,085; 3,097) | 604 (−1,194; 2,403) | −1,517 (−5,364; 2,330) | 316 (−2,052; 2,684) | 2,736 (−1,922; 7,394) | 1,915 (−1,159; 4,989) | 4,150 (−1,368; 9,669) | 2,902 (−964; 6,767) | 11,112 (−17,109; 39,333) |

*(Continued)*

TABLE 3 (Continued)

| Country | 2020 | | 2021 | | 2022 | | 2023 | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | Males | Females | Males | Females | Males | Females | Males | Females | |
| **SE** | **76,269 (19,775; 132,764)** | **31,022 (8,791; 53,253)** | **114,790 (49,666; 179,914)** | **44,940 (17,342; 72,538)** | **83,097 (8,089; 158,105)** | **32,016 (−1,675; 65,708)** | **57,410 (−28,765; 143,585)** | **14,785 (−25,871; 55,440)** | **454,329 (47,350; 861,307)** |
| Croatia | 325 (−1,805; 2,455) | 655 (−252; 1,563) | 6,273 (3,618; 8,928) | 4,004 (2,707; 5,301) | 1,815 (−1,554; 5,184) | 767 (−934; 2,468) | −420 (−4,549; 3,710) | 343 (−1,769; 2,455) | 13,763 (−4,538; 32,064) |
| Cyprus | 387 (−188; 962) | 425 (7; 843) | 1,607 (669; 2,544) | 832 (226; 1,438) | 272 (−1,046; 1,589) | 300 (−531; 1,131) | 706 (−1,013; 2,425) | 106 (−972; 1,183) | 4,634 (−2,847; 12,115) |
| Greece | 805 (−3,325; 4,934) | 3,087 (1,231; 4,944) | 18,807 (13,224; 24,390) | 8,261 (5,885; 10,637) | 3,692 (−3,252; 10,636) | 2,578 (−391; 5,547) | −4,223 (−12,592; 4,146) | 1,111 (−2,532; 4,754) | 34,118 (−1,752; 69,988) |
| Italy | 26,970 (9,197; 44,744) | 9,884 (2,446; 17,323) | 45,210 (25,947; 64,473) | 18,015 (8,783; 27,247) | 35,002 (13,634; 56,370) | 13,472 (2,057; 24,886) | 34,224 (10,488; 57,961) | 10,258 (−3,592; 24,109) | 193,036 (68,960; 317,112) |
| Malta | 677 (203; 1,152) | −248 (−558; 62) | 514 (−272; 1,299) | −395 (−880; 90) | 860 (−268; 1,987) | −392 (−1,074; 289) | 197 (−1,413; 1,806) | −605 (−1,517; 308) | 608 (−5,779; 6,995) |
| Portugal | 10,544 (3,233; 17,854) | 1,024 (−1,324; 3,371) | 9,028 (609; 17,446) | 1,857 (−1,549; 5,263) | 9,312 (−439; 19,063) | −163 (−4,708; 4,381) | 6,966 (−4,361; 18,294) | −1,716 (−7,504; 4,072) | 36,851 (−16,042; 89,745) |
| Slovenia | 652 (−950; 2,254) | 645 (39; 1,250) | 1,800 (−329; 3,929) | 613 (−273; 1,498) | 1,142 (−1,496; 3,780) | 1,315 (128; 2,503) | 488 (−2,696; 3,672) | 837 (−667; 2,342) | 7,492 (−6,244; 21,228) |
| Spain | 35,909 (13,409; 58,409) | 15,549 (7,201; 23,897) | 31,552 (6,199; 56,904) | 11,753 (2,442; 21,063) | 31,003 (2,510; 59,496) | 14,140 (3,777; 24,504) | 19,470 (−12,630; 51,570) | 4,450 (−7,316; 16,217) | 163,827 (15,592; 312,061) |
| **WE** | **55,815 (−23,004; 134,634)** | **3,465 (−28,039; 34,969)** | **139,954 (50,804; 229,105)** | **32,292 (−5,633; 70,216)** | **149,810 (48,671; 250,950)** | **44,673 (−1,071; 90,416)** | **108,678 (−6,596; 223,952)** | **17,172 (−37,620; 71,964)** | **551,858 (−2,489; 1,106,206)** |
| Austria | 1,559 (−3,135; 6,253) | −770 (−2,435; 896) | 9,339 (3,824; 14,855) | −166 (−2,642; 2,309) | 7,059 (627; 13,491) | −29 (−3,351; 3,294) | 5,641 (−1,940; 13,222) | 28 (−4,232; 4,288) | 22,662 (−13,284; 58,609) |
| Belgium | 5,978 (−28; 11,984) | 1,247 (−1,918; 4,412) | 6,699 (−225; 13,623) | 4,092 (355; 7,829) | 7,307 (−601; 15,214) | 3,166 (−1,222; 7,555) | 3,610 (−5,372; 12,591) | 2,471 (−2,717; 7,658) | 34,570 (−11,727; 80,867) |
| France | 15,257 (−12,160; 42,674) | 1,801 (−6,117; 9,718) | 35,866 (4,312; 67,420) | 1,618 (−8,557; 11,793) | 45,919 (9,728; 82,110) | 9,389 (−3,368; 22,146) | 32,848 (−8,266; 73,962) | 1,419 (−14,037; 16,875) | 144,116 (−38,465; 326,698) |
| Germany | 25,716 (−9,387; 60,818) | −587 (−14,241; 13,068) | 75,637 (37,244; 114,031) | 17,789 (2,294; 33,284) | 77,944 (35,559; 120,329) | 24,046 (6,013; 42,078) | 56,368 (8,607; 104,128) | 8,806 (−12,422; 30,033) | 285,718 (53,667; 517,770) |
| Luxembourg | −198 (−647; 250) | 37 (−291; 366) | −294 (−1,006; 417) | 285 (−231; 801) | −238 (−1,250; 775) | −8 (−729; 712) | −339 (−1,675; 998) | −37 (−987; 912) | −793 (−6,816; 5,230) |
| Netherlands | 7,503 (2,353; 12,654) | 1,736 (−3,037; 6,509) | 12,707 (6,655; 18,758) | 8,674 (3,148; 14,200) | 11,819 (4,608; 19,031) | 8,109 (1,585; 14,632) | 10,550 (2,050; 19,050) | 4,485 (−3,227; 12,197) | 65,584 (14,136; 117,032) |

*(Continued)*

TABLE 3 (Continued)

| Country | 2020 | | 2021 | | 2022 | | 2023 | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | Males | Females | Males | Females | Males | Females | Males | Females | |
| **Total** | **291,806 (59,723; 523,889)** | **86,548 (−443; 173,539)** | **659,282 (390,134; 928,430)** | **240,961 (132,844; 349,078)** | **378,032 (66,622; 689,443)** | **124,135 (−8,720; 256,990)** | **180,808 (−179,940; 541,556)** | **35,523 (−125,277; 196,323)** | **1,997,095 (334,943; 3,659,247)** |

Each cell contains a point estimate and a 95% confidence interval in brackets. CEE, Central and Eastern Europe; NE, Northern Europe; SE, Southern Europe; WE, Western Europe. Bold font represents total values for countries within each of four European regions.

42.3% of total eYLL were among those aged 75 + (34.8% in males and 52.8% in females; Supplementary Table S7). For the non-old population (aged <60), the share of total eYLL was 23.8% and was higher in males (29.6%) than in females (15.9%). Generally, the share of eYLL from the deaths of those aged <60 increased with time in both men (2020: 20.0%; 2023: 44.7%) and women (2020: 9.8%; 2023: 14.1%).

As for working-age population losses, the most burdened age groups were 40–44, 45–49, and 50–54 (Supplementary Table S8), with those aged <45 and 45 + contributing around 42 and 58% of all eYPPLL across all the countries and years, respectively. Similarly to years lost in the general population, we note a time-increasing share of losses in the younger sub-population (aged <45); in 2020, this group contributed 31.2% of total eYPPLL in males and 31.8% in females, while in 2023, the respective shares were 64.4% in males and 80.9% in females (Supplementary Table S9).

## 3.6 Comparison of excess and COVID-19 deaths

Figures 4, 5 compare the number of excess deaths with the number of deaths due to COVID-19 in five-year age groups. We note notable differences among countries in comparing the two mortality measures. For countries as Belgium, Czechia, France, Ireland, or Spain, the COVID-19 deaths constitute a notable proportion of excess deaths (particularly in the older population), while in other territories as Finland, Portugal, Romania or Slovakia, the share of fatalities with a COVID-19 diagnosis assigned was very low. Additionally, the comparison shows that in some countries and age groups, particularly among the youngest (0–4, 5–9, 10–14, 15–19), the COVID-19 pandemic had a protective effect, reflected in reduced mortality. For example, in Sweden, we observed reduced deaths in the age groups 20–24, 25–29, 30–34 and 35–39.

## 3.7 Results of sensitivity analysis

To assess the robustness of expected mortality rate estimates, we compared the final specification (S2: short-baseline linear trend) with three alternative OLS (S1, S3, S4) and two time-series specifications (ARIMA and ETS), summarising absolute percentage deviations in age groups (Supplementary Table S10). Deviations for S1, S3, ARIMA and ETS were generally modest, with median differences around 3–5%. In contrast, the short-baseline quadratic model (S4) showed systematically larger discrepancies and substantially wider IQRs. As expected, deviations were greatest in age groups with very low mortality, where small absolute differences translate into large proportional changes.

A consistent age gradient emerged; in the 0–24 group, median deviations ranged from 8 to 13% for the linear and time-series models but exceeded 23% for S4. In working ages (25–64), deviations were considerably smaller, with S4 again showing the largest divergence (median 7.2%). At older ages (65+), all models remained close to the baseline, indicating stable forecasts where death counts are higher. Overall, these patterns show that quadratic specifications, especially S4, are prone to instability in low-mortality groups, while linear and time-series models remain close to the chosen baseline.

For life-years metrics, projected 2050 LE increased total eYLL by 15.5%, with proportionally larger rises in CEE and smaller changes in SE. These shifts affected magnitudes but did not alter the regional ranking of excess life-years lost. For eYPPLL, restricting productive ages to 20–64 changed results only marginally (+2.2% overall), with most countries remaining within ±10% of the baseline (Supplementary Table S11). Both sets of metrics, therefore, remain qualitatively stable across alternative assumptions.

# 4 Discussion

Our analysis of 28 European countries revealed 1.54 million excess deaths (eD), 16.7 million excess years of life lost (eYLL), and 2.0 million excess years of potential productive life lost (eYPPLL) between 2020 and 2023. The highest standardised excess mortality rates were observed in Central and Eastern Europe, particularly in Bulgaria, Romania, Slovakia, Poland, Lithuania and Latvia, while the lowest were in the Nordic countries (Norway and Denmark). In general, men experienced a higher excess mortality burden than women, and this difference was more pronounced in eYLL and eYPPLL, highlighting a higher mortality burden in younger-aged men. These findings are consistent with those reported elsewhere, regardless of the estimation method and data sources used (15, 17, 41–42).

The analysis by Pizzato et al. (17) showed a similar number of eD between 2020 and 2023. In absolute terms, the countries most burdened by excess mortality in our study align with those identified in (17) (Italy, Poland, Germany, France and Spain in the same order in both studies). Our estimate of eYLL is akin to the 16.8 million person-years of life lost (PYLL) reported for 18 European countries (41); however, although the results are very similar, they are not directly comparable because of differences in geographical scope (28 vs. 18 countries), methodology (all ages vs. population aged 35 and over, and forecasting approach), and the inclusion of the full year 2023. To benchmark our estimates further, Supplementary Table S12 compares our excess deaths with several influential multi-country studies, covering three reference periods: 2020 only, 2020–2021, and 2020–2023. For the most comparable interval, 2020–2021, our

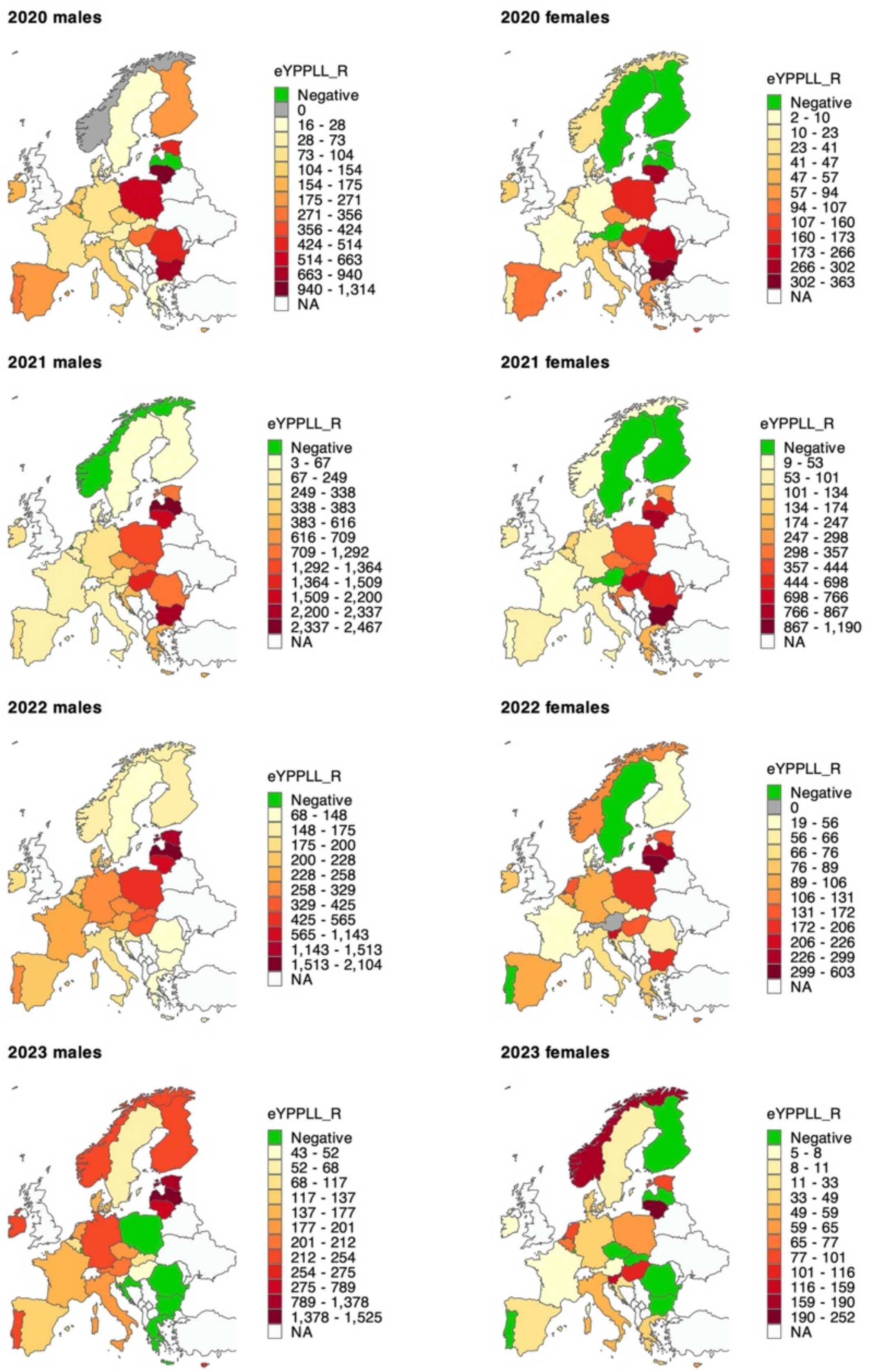


FIGURE 3
Age-standardised excess years of potential productive life lost per 100,000 working population in 28 countries in 2020–2023. Detailed results with confidence intervals are available in Supplementary Table S3. eYPPLL_R—age-standardised excess years of potential productive life lost rate per 100,000 population. Each map uses its own colour scale because the magnitude of excess years of potential productive life lost varies substantially across years (e.g., 2021 shows much higher values than 2023) and sexes.

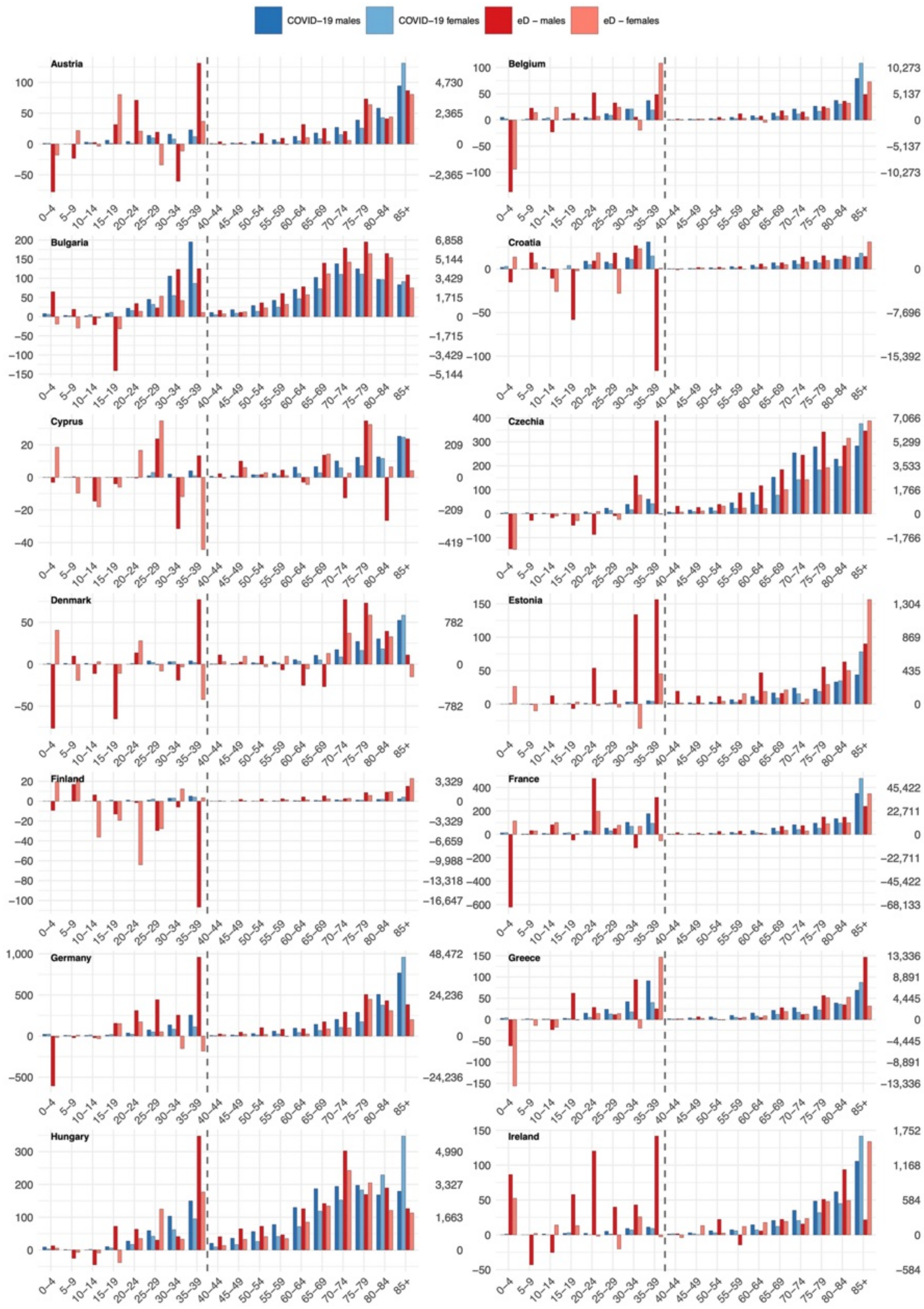


FIGURE 4
Comparison of excess deaths (eD) and COVID-19 deaths across 5-year age groups, part 1/2. The figure uses two separate scales; the left one for the younger (0–39 years) and the right one for the older (40–85+). This figure illustrates age-specific differences in cumulative excess mortality and COVID-19 mortality over the entire 2020–2023 period. Annual variations and early/late pandemic differences are only exhibited for excess mortality in Figures 1–3 and Tables 1–3.

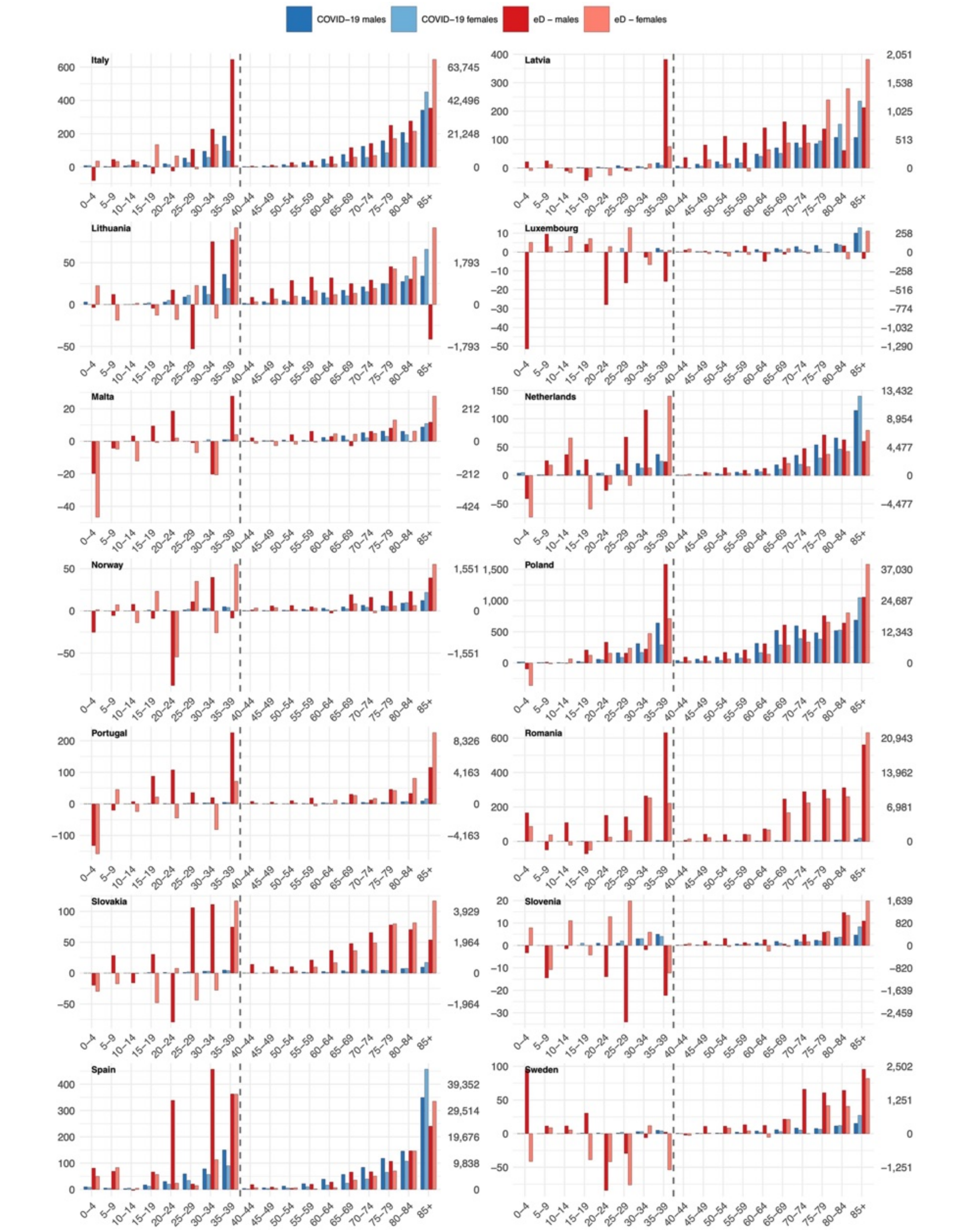


FIGURE 5
Comparison of excess deaths (eD) and COVID-19 deaths across 5-year age groups, part 2/2. The figure uses two separate scales; the left one for the younger (0–39 years) and the right one for the older (40–85+). This figure illustrates age-specific differences in cumulative excess mortality and COVID-19 mortality over the entire 2020–2023 period. Annual variations and early/late pandemic differences are only exhibited for excess mortality in Figures 1–3 and Tables 1–3.

findings are broadly consistent with those reported by others, with notable differences concentrated in a few countries such as Denmark, Norway, and Sweden, where small absolute changes in mortality and differing baseline specifications can lead to appreciable variation across studies. Our estimate for Germany in 2020–2021 (64,619 eD) is also lower than several published estimates, which range 88–203 thousand eD (Supplementary Table S12). However, our figure aligns with the age-adjusted estimate of Levitt et al. (14), who reported 54,740 eD for the same period. In contrast, their unadjusted estimate was 128,557 deaths, underscoring that age composition plays a substantial role in excess mortality calculations. The close correspondence between our 5-year age-group modelling framework and the age-adjusted results of Levitt et al. supports the validity of our age-structured approach. Therefore, the greatest divergence across studies was identified for countries with small populations or low excess mortality (e.g., Denmark, Norway, Sweden, Luxembourg, Malta), where even minor differences in baseline specification or age adjustment can generate large discrepancies. In contrast, estimates were much more consistent for large countries such as Italy, France, Poland, and Spain, reinforcing the stability of excess mortality calculations at larger scales.

Among Europeans of working age (20–64 years), the total eYPPLL was 1,997,095, representing 12.0% of the total eYLL, highlighting the significant impact of the pandemic on mortality among those aged 65 and older. We found no studies evaluating the years of potential productive life lost due to excess mortality in the working population caused by COVID-19. This emphasises the importance of our study in understanding COVID-19's effects on working-age individuals.

The higher excess mortality among men aligns with the findings of Beegle et al. (44), which showed that in high-income countries, men died on average 2.2 times more often in 2020 and 1.8 times in 2021; yet, the magnitude of the variation depended on age structure and comorbidity burden. Other studies also support this unfavourable tendency in men (12, 41–43, 45, 46). An additional interesting finding from (44) is that the average male-to-female mortality ratio was higher for eD than for expected all-cause deaths in both 2020 and 2021. Our data suggest that this pattern extends beyond the number of deaths; specifically, the number of eD in men is 21.4% higher than in women, the number of eYLL in men is 38.1% higher, and the number of eYPPLL in men is 209.9% higher. This means that more men died at younger ages, and the difference was particularly strong at working ages. Possible explanations include biological differences (such as immune response), a higher prevalence of risk factors (smoking, alcohol intake and chronic diseases), and greater occupational exposure (47–52). However, as pointed out previously (46), differences in excess mortality between males and females are not unique to the COVID-19 pandemic but are characteristic of any excess mortality.

The greatest losses were identified in the age groups 80–84 and 85 + for eD, 65–69 and 75–79 for eYLL, and 45–49 and 50–54 for eYPPLL. Compared to (41), our study shows notable differences in how years of life lost are distributed; in our analysis, 42.3% of total eYLL was in the 75 + age group, while the younger population (under 60) accounted for 23.8%, which sharply contrasts with the 30% of total years of life lost in the 65–80 age group and 60% in those aged 80 and older in (41). Our detailed age-specific findings show that COVID-19 does not spare the working-age population. Although most deaths occurred among the older population, a significant burden was identified in younger age groups, especially those aged 40–54. Also, the burden in the younger population was geographically disproportionate, with CEE and Baltic states (Latvia, Lithuania and Estonia) experiencing the heaviest death toll. This crucial finding calls for further analysis of excess mortality among the working population, since European states face severe labour shortages undermining economic growth (16).

After a record high mortality in 2021, the excess rates declined but remained above zero in most countries in 2023. Although the number of eD in 2023 was 77% lower than in 2020, this situation highlights that the ongoing indirect pandemic's impacts persist, even with widespread COVID-19 vaccination efforts (53). The results of the cross-country study (17) also support our findings, showing the highest burden in 2021. The other research (41) indicated that the years of life lost due to COVID-19 decreased over time since the start of the pandemic, while the years of life lost from other causes increased. A regional study (42) showed that in 2021, the highest cumulative loss of life years was almost entirely concentrated in CEE, while some Western regions experienced gains in life years. A study covering 13 WE countries (54) identified significant variations in cumulative mortality between the countries analysed—those with faster non-pharmaceutical interventions (NPIs) responses and higher vaccination enrollment (e.g., Denmark) had lower age- and sex-standardised cumulative excess mortality. The link between timely vaccination coverage and reduced excess mortality is well documented. Another cross-European study (53) found that the average excess mortality in the countries with slower vaccination rollout (less than 70% vaccination coverage by January 2022) was nearly five times higher than in those with faster rollout (more than 70% vaccination coverage by January 2022).

Our results confirm geographic differences in the pandemic burden. The largest East–West gradient was observed in 2021, consistent with the results of the studies by Bonnet et al. (42) and Pizzato (17). In 2022, the gradient between East and West countries persisted, but in 2023, the situation changed. We identified the negative excess mortality in 2023 in countries that were among the most burdened in 2020–2022 (Bulgaria, Hungary, Romania, and Lithuania, among others). This gradient might result from worse structural and psychosocial factors in the CEE post-transitional countries, leading to higher mortality therein (55). A magnitude of socio-economic factors was outlined in the study (17) which found that lower GDP per capita, higher poverty levels, and lower healthcare spending correlated with greater excess mortality, while vaccination coverage had a protective effect on mortality.

The East–West mortality divergence, the persistence of excess mortality in most countries in 2023, and the negative excess mortality in 2023 in countries heavily affected during the COVID-19 pandemic may stem from several factors. Firstly, a sustained increase in mortality following the pandemic was related to long-term health complications caused by the virus (56, 57), but also disruptions in healthcare services such as missed cancer screenings and delayed surgeries (58–60). Additionally, emerging mental health issues resulting from social isolation measures and pandemic-borne fears plausibly played a role (61). Secondly, the harvesting effect suggests that the virus mainly impacted the most vulnerable individuals, potentially resulting in decreased mortality in the post-pandemic period (7). Thirdly, the reverse harvesting effect (7) or dry tinder hypothesis (62) suggest that at the pandemic onset, NPIs protected the most vulnerable from seasonal infections that could have led to death. In later years, as restrictions were eased, an increased mortality was observed among the most vulnerable due to infections other than COVID-19.

As for the comparison of excess deaths and COVID-19 deaths in particular countries, the differences identified in our study are in line with Sanmarchi et al.'s study (63) showing that countries differ notably in their capabilities to test, diagnose, and certify COVID-19 deaths. Therefore, excess mortality exceeded confirmed COVID-19 mortality, particularly in countries with lower testing capacity or more restrictive diagnostic practises, including several Eastern European countries or Portugal, among others. On the other hand, countries with more efficient certification systems and broader inclusion of suspected COVID-19 deaths, such as Belgium, France or Spain, showed smaller gaps between the two mortality measures.

The sensitivity analyses indicate that our findings are robust to alternative modelling and conceptual assumptions. Alternative linear and time-series models produced only minor deviations from the selected specification, but quadratic trends, particularly using short baseline, showed instability in low-mortality young age groups, reinforcing the choice of a linear specification. Likewise, although extending LE assumptions increased absolute eYLL levels, and adjusting productive-age ranges slightly shifted eYPPLL, these variations did not alter the relative ranking of countries. Together, these results demonstrate that our findings are not sensitive to modelling choices or scenario assumptions.

Before we conclude, we shall acknowledge the strengths and limitations of our analysis. For strengths, we analysed a comprehensive set of excess mortality measures, including excess death counts, eYLL and eYPPLL, capturing not only the epidemiological burden of excess deaths but also the economic dimension of these losses. Also, we used detailed 5-year age groups, unravelling patterns unobservable in studies using all-age or wide age intervals. Additionally, we analysed a set of 28 countries through the year 2023, allowing for assessment of the post-pandemic situation and relied on complete and final death statistics from Eurostat, not short-term data that requires verification. Moreover, we reduced arbitrariness in baseline selection by evaluating multiple baseline windows and trend specifications and selecting the final forecasting model using selection criteria. Eventually, we evaluated model robustness using alternative specifications and forecasting methods through sensitivity analysis, supporting the stability of our findings.

Several limitations should be acknowledged. First, we used annual data, which limited modelling choices, leading to reliance on annual OLS trend models evaluated across multiple baseline windows and specifications. Consequently, the confidence intervals for our estimates are fairly wide; yet, this shortcoming is not unique to our study, as several prior analyses reported results of even larger uncertainty (15, 25, 32). Second, the estimates for low-populated countries should be treated with caution, as the small number of deaths leads to greater statistical uncertainty and increased risk of random variation affecting the estimates. Third, we used all-cause mortality data and did not account for the causes of death. Fourth, the methodological choice regarding eYLL and eYPPLL might have affected our findings; therefore we addressed this last limitation through sensitivity analysis. Fifth, aggregated estimates implicitly treat forecast errors across age groups as independent, which may lead to conservative uncertainty intervals. Sixth, although we accounted for mortality-model uncertainty when estimating eYLL and eYPPLL, additional uncertainty arising from future life expectancy changes or evolving labour market participation patterns was not formally quantified and was therefore addressed only through scenario-based analyses. Finally, excess mortality in 2023 may partly reflect non-COVID factors, such as heatwaves, influenza resurgence, or health systems disruptions, which were not examined in this study and may contribute to the observed post-pandemic mortality burden.

## 5 Conclusion

Our results show that COVID-19 has exacerbated existing demographic inequalities in Europe, particularly between East and West and between sexes. Although the pandemic mortality burden has generally decreased, it was still identified in 2023, requiring further preventive and systemic actions. The persistence of excess mortality in 2023 likely reflects a combination of long-term pandemic effects and non-COVID factors. Integrating health and economic indicators, such as the eD, eYLL and eYPPLL, should become an element of public health policy to better recognise different dimensions of mortality burden and to prepare for future health crises.

As for health policy implications, CEE should prioritise efforts towards improving their health care systems and vaccination acceptance to limit excess health burden in future. Further, the countries should maintain monitoring efforts; although excess rates are declining, they remained positive in 2023 in several states, underscoring the need for long-term surveillance of the pandemic's consequences. Importantly, our estimates of productive-life losses show that the economic burden of the pandemic is substantial. The future research efforts should assess this burden in monetary terms to inform policymakers on how much Europe lost through production uncompleted due to excess mortality, as cross-country evidence in this respect is scarce (64).

## Data availability statement

Publicly available datasets only were analysed in this study. This data can be found here: Eurostat databases (18–20).

## Ethics statement

The study did not involve humans and was approved by Ethics Committee of the Nicolaus Copernicus University in Toruń, Collegium Medicum in Bydgoszcz (24/10/2023; no. KB 425/2023). The study was conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not applicable as no humans were involved in the study.

## Author contributions

PN: Data curation, Writing – original draft, Conceptualization, Methodology, Visualization, Investigation, Formal analysis, Writing – review & editing. JW: Formal analysis, Writing – original draft. BŁ: Writing – review & editing, Supervision, Conceptualization, Methodology.

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## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The author(s) declared that Generative AI was used in the creation of this manuscript. ChatGPT (version 5.1) was used exclusively for language editing and readability of the manuscript. The authors are fully responsible for the study design, data analysis, interpretation, and all scientific conclusions.

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## Publisher's note



## Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2025.1720864/full#supplementary-material

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ORIGINAL PAPER

# Paid and unpaid productivity losses across 28 European countries due to excess deaths and COVID-19 deaths from 2020 to 2023

**Paweł Niewiadomski[1] · Marta Ortega-Ortega[2] · Błażej Łyszczarz[3]**

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## Abstract

**Background** The COVID-19 pandemic has caused significant epidemiological and economic burdens. Although extensive epidemiological research exists, data on productivity losses resulting from COVID-19 remain limited. Therefore, this study aimed to estimate paid and unpaid productivity losses from excess deaths and COVID-19 deaths across 28 European countries from 2020 to 2023.

**Methods** This study used retrospective, population-level Eurostat data and a societal perspective to estimate paid and unpaid productivity losses (indirect costs) related to mortality caused by the COVID-19 pandemic (excess deaths and COVID-19 attributable deaths) in 28 European countries (European Union and Norway) from 2020 to 2023. For paid (market) losses, we applied the alternatives of the human capital approach (HCA) and the friction cost approach (FCA); for unpaid (non-market) losses, we used the opportunity cost approach (OCA).

**Results** Total paid productivity losses from excess deaths in 2020–2023 across all 28 countries combined were €57.6 billion in the Human Capital Approach and €3.1 billion in the Friction Cost Approach. Unpaid productivity losses amounted to €72.5 billion, of which €19.6 billion were attributable to the employed and €52.9 billion to the non-employed. For COVID-19 deaths, the productivity losses were lower: €35.0 billion for HCA, €2.1 billion for FCA, and 56.2 billion for unpaid losses (€12.4 billion for the employed, and €43.8 billion for the non-employed). The highest relative economic burden was experienced in the Central and Eastern European countries and three Baltic states (Latvia, Lithuania and Estonia). Losses were higher among men than women, particularly in paid productivity losses (> 80% of total). Age-specific paid losses and unpaid losses among the employed were the greatest in the middle-aged (40–59), while for unpaid losses among non-employed, most of the burden was identified in the elderly (aged 60–74). Additionally, we identified heterogeneous time patterns across regions, with Central and Southern European countries experiencing the highest losses in 2021, Western countries in 2022 and Northern ones in 2023.

**Conclusions** This study shows that the burden of productivity losses caused by pandemic mortality was substantial, highly variable across regions and over time, and sensitive to the baseline mortality and valuation method used.

**Keywords** Productivity losses · COVID-19 · Excess deaths · Mortality · Human capital approach · Friction cost approach · Opportunity cost approach · Indirect costs · Europe



✉ Paweł Niewiadomski
pawel.niewiadomski@doktorant.umk.pl

1 Doctoral School of Medical and Health Sciences, Nicolaus Copernicus University in Toruń, Bydgoszcz, Poland

2 Department of Applied and Public Economics, and Political Economy, Complutense University of Madrid, Madrid, Spain

3 Department of Health Economics, Nicolaus Copernicus University in Toruń, Bydgoszcz, Poland

**Abbreviations**

| | |
|---|---|
| CD | COVID-19 deaths |
| CEE | Central and Eastern Europe |
| CIT | Corporate income tax |
| ED | Excess deaths |
| EU | European Union |
| FCA | Friction cost approach |
| GDP | Gross domestic product |
| GVA | Gross value added |
| HCA | Human capital approach |
| NE | Northern Europe |

| | |
|---|---|
| OCA | Opportunity cost approach |
| OCAe | Opportunity cost approach for the employed |
| OCAn | Opportunity cost approach for the non-employed |
| OLS | Ordinary least squares |
| PIT | Personal income tax |
| SE | Southern Europe |
| VAT | Value added tax |
| WE | Western Europe |

## Background

Burden of disease studies on COVID-19 have provided a comprehensive picture of the pandemic's health toll in terms of both mortality and morbidity [1, 2]. Numerous analyses have documented declines in life expectancy [3, 4], excess mortality [5, 6], and reported on morbidity-related outcomes such as disability-adjusted life years [7]. In contrast, comparative evidence on the broader socio-economic consequences of this health deterioration remains limited.

One under-researched area of the COVID-19 economic burden is the estimation of productivity losses resulting from the pandemic [8]. The productivity losses, also referred to as indirect costs, represent the potential economic output foregone as a result of disease. As such, productivity losses estimates provide complementary information to burden of disease studies [9, 10]. While the burden of disease studies estimate health impacts, productivity losses analyses translate those impacts into economic terms, quantifying the economic output lost due to morbidity and premature mortality. Although the two approaches are conceptually distinct, together they provide a more comprehensive assessment of the societal burden of disease.

A recent worldwide systematic review of population-level studies on COVID-19 productivity losses identified major research gaps in the literature [11]. First, the methodological approaches used were limited; most studies employed the human capital approach (HCA) exclusively. While some economic evaluations and cost-effectiveness analyses have incorporated productivity losses using alternative valuation methods, population-level studies estimating mortality-related productivity losses using the friction cost approach remain very limited [12, 13], particularly in a cross-country European context. Second, few studies (e.g. [14]) provided population-level estimates of unpaid productivity losses that arise in non-market settings, such as household or volunteer production lost due to the disease. Third, evidence often covered only the early phase of the pandemic and rarely captured long-term COVID-19 effects that persist also post-pandemic. Fourth, cross-country comparisons of productivity losses remain difficult due to differences in study design, calculation methods, and time horizons. This impedes direct comparison of losses in various time and geographical settings. Finally, few studies incorporated the notion of excess mortality [14, 15], as most of the evidence focused strictly on COVID-19 mortality [11]. This contrasts with epidemiological literature, which has highlighted excess deaths as a key indicator of the pandemic's health burden [16, 17].

This study addresses these gaps in population-level analyses by estimating productivity losses from both COVID-19 and excess mortality in 28 European countries in pandemic and post-pandemic years, 2020–2023. Using Eurostat data and a unified methodology, we provide highly comparable, cross-country evidence. Our analysis contributes to the literature in three key ways: it investigates both paid (market) and unpaid (non-market) productivity losses; it compares results based on the HCA and the FCA; and it extends beyond single-country assessments by covering a wide range of European states. Moreover, we report an additional economic burden category of public revenue losses. Together, these contributions enhance understanding of the COVID-19 economic toll and support evaluation of pandemic-related policy responses.

Therefore, this study aimed to estimate paid and unpaid productivity losses from excess deaths and COVID-19 deaths in 28 European countries in the 2020–2023 period, using a uniform methodology based on highly comparable Eurostat data. By providing estimates based on this approach, our study offers policymakers robust evidence on the economic burden of the pandemic across Europe. These findings may provide policy-makers with a better understanding of the recent pandemic economic costs and inform evidence-based decisions regarding future pandemic preparedness and mitigation of societal impacts of health crises [18].

## Methods

### General approach

This study used retrospective, population-level data and a societal perspective [19, 20] to estimate productivity losses (indirect costs) associated with mortality attributable to the COVID-19 pandemic in 28 European countries (European Union and one country of the European Economic Area (EEA), Norway) in 2020–2023. The country choice was determined by the completeness of population-level Eurostat data required for the study, including age- and sex-specific mortality, employment rates, earnings, and time-use information used to value unpaid production. Other EEA countries (Iceland and Liechtenstein) were excluded due to incomplete data for one or more of these components over the 2020–2023 period.

Productivity losses represent an economic output unproduced [9, 21] due to mortality associated with the COVID-19 pandemic.

We use two alternative approaches to define mortality attributable to COVID-19: (a) deaths reported with the ICD-10 code U07 assigned as a cause of death; and (b) excess deaths. For both approaches, we estimate paid and unpaid productivity losses [22]; the former represent formal losses from market activities undone, and the latter account for non-formal output lost. For paid losses, we rely on two alternative loss estimation methods, the human capital approach (HCA) and the friction cost approach (FCA). For unpaid losses, we use the opportunity cost approach (OCA). All these methods are explained in detail below.

Following a recent systematic review of COVID-19 productivity losses [11], we report results broken down by sex and three age-based groups: the young (0–39 years), middle-aged (40–59 years), and elderly (60+years).

Data preparation and structuring were performed in Microsoft Excel 2021. Excess mortality estimation was conducted in Python (v. 3.11.6) using pandas (2.2.3), numpy (2.2.1) and statsmodels (0.14.4). Productivity loss calculations were carried out in Microsoft Excel, while graphical outputs were produced in R (v. 4.4.1) using RStudio (v. 2024.09). The use of multiple software environments reflected task-specific efficiency and facilitated data handling and analysis.

## Mortality attributable to COVID-19

Country-specific Eurostat annual data on all-cause deaths [23] and COVID-19 deaths [24] (both broken down by sex and 5-year age groups), were used to determine excess deaths and deaths attributable directly to the virus, respectively. For excess deaths, we used age-group- and sex-specific mortality rates from the 2002–2019 baseline period to build Ordinary Least Squares (OLS) regression models, allowing us to predict mortality rates during the pandemic and post-pandemic years, 2020–2023. To avoid arbitrariness in baseline selection and trend specification, we applied a multiverse modelling approach, estimating all possible consecutive pre-pandemic baseline periods ending in 2019 and evaluating alternative linear and quadratic time-trend specifications. For each country, sex, and age group, forecasts for 2020–2023 were generated across all baseline windows and model specifications. Extreme predictions arising from short or unstable baselines were excluded using a Tukey 1.5 interquartile range criterion [25], and remaining forecasts were averaged to obtain expected mortality. Model performance was assessed using pre-pandemic goodness-of-fit criteria (Akaike Information Criterion, Mean Absolute Error, and Root Mean Squared Error), and a single specification was selected uniformly across strata based on overall performance. Expected deaths were obtained by multiplying predicted mortality rates by observed population counts, and excess deaths were calculated as the difference between observed and expected deaths. Methodological details, diagnostics, and robustness analyses are provided in a dedicated epidemiological study [26].

Because we used 5-year age groups, we assumed that each death occurs at the midpoint of a group, e.g. at the age of 27 for the 25–29 age group. Although Eurostat data on all-cause deaths (used to assess excess mortality) are available in single-age groups, we aggregated these counts into 5-year groups. This is because COVID-19 death counts and key economic inputs (e.g. employment rates) are available only in 5-year age groups; therefore, all analyses were conducted using this age structure. Also, the use of 5-year age groups improves statistical stability in low-population countries at younger ages, where single-year counts are very low or zero [26, 27]. The impact of age-group assignment was assessed in a sensitivity analysis, as described below. Additionally, a half-cycle adjustment was applied, meaning that all deaths occurred in the middle of the year [28] (not in the FCA, where this adjustment was irrelevant).

## Economic measures

A productivity measure applied was per worker gross domestic product (GDP) adjusted for purchasing power parity [29]. Because the per worker GDP reflects average economic output and indirect cost estimation should rather rely on marginal, not average productivity [21, 30], we adjusted per worker GDP by a 0.65 coefficient that approximates the output elasticity of labour as used in the European context [31] (for applications, see [32, 33]).

To account for productivity variation across age- and sex-specific sub-populations, we used available Eurostat data on mean annual earnings [34]. We assume that the variation of per worker GDP between particular age groups and sexes might be reflected by respective differences in earnings between sub-populations defined as such. In detail, we used three age groups as reported by Eurostat: <30, 30–49, and ≥50 years of age for each of the 28 states analysed. For example, in Belgium, earnings of men (women) aged <30 (50+) are 31.2% lower (15.7% higher) than on average for men (women), and we assume that the productivity measure (per worker GDP) varies accordingly.

In contrast to previous studies [22, 32], we do not estimate losses in the strictly working-age population (using either factual or legal retirement age as a threshold for quitting the labour market). Instead, we include the population at each age for which employment rates are reported by Eurostat [35], meaning that the population aged 15–74 years is analysed here. Employment rates were applied in 5-year age groups (15–19, 20–24, …, 70–74), explicitly capturing the sharp decline in labour market participation at older ages.

For the HCA and OCA estimates, we used a 5% discount rate to account for the diminishing future value of production lost. Additionally, to incorporate the impact of future economic growth across the EU, we used the EU average potential per worker GDP growth rates for the forthcoming decades [36]. For FCA, neither discounting nor economic growth adjustment was applicable because, for this method, losses do not extend into the future to more than a year.

All the losses were expressed in real terms, using the harmonised index of consumer prices as a deflator [37] and 2020 as a base year.

## Human capital approach

Using the HCA, productivity losses represent the potential discounted value of market output lost (paid losses) that would be produced if those who died were still alive and were working until the end of their projected labour market activity period. To adjust for variations in employment participation and productivity between sexes and populations across different age, we used sex- and age-specific input data for employment rates and per worker GDP, as explained above. Subsequently, productivity losses were estimated by incorporating the progressive variability of per worker GDP and employment rates, which change by sex and age group. Specifically, the calculations reflected the fact that productivity tends to increase with age, while labour market participation declines in the elderly.

Unlike most of the studies that deal with COVID-19-related deaths in the working age population (see e.g. [14, 38, 39]), we included deaths at pre-productive age (age groups 0–4, 5–9, 10–14). This is because those dying young would eventually enter the labour market, and the potential economic output lost due to these deaths should be accounted for (adjusting for expected employment rates and the discounted value of future productivity). For example, as we assume that labour market entry occurs at the age of 15, a 2020 death in the age group 0–4 would result in employment entry in 13 years (15—2 [middle of the age range] = 13), that is, in 2033.

## Friction cost approach

The friction cost approach offers an alternative to the HCA for assessing productivity losses attributable to diseases. FCA assumes that the productive time lost due to illness is limited only to the period needed to replace a deceased worker, allowing for production restoration with this replacement [10, 30].

For the calculation of the friction period, we relied on the study [40], which estimated the friction period in 30 European countries. Using their base-case method ($I_{BC}$) for each country and year, we obtained respective friction periods. Estimates of productivity losses based on the FCA were limited to the population aged 15–74, meaning that the pre-productive population was excluded. This is because the FCA, unlike the HCA, does not deal with losses of those anticipated to start work in future. We used sex- and age-specific input data, as we do in the HCA. Accordingly, productivity losses are calculated as the product of the number of deaths and per worker GDP corresponding to the country- and year-specific friction period.

## Opportunity cost approach

The OCA is used to estimate losses from unpaid production. This indirect cost category represents the non-market production uncompleted by those (working in the labour market or not) who domestically undertake productive tasks that have societal value and could be monetised according to market rates [22]. A single category of unpaid production was created by summing up the time spent (based on Eurostat's Time Use Survey 2010 [41]; no more recent edition available) on several categories, including household and family care, laundry, among others1[1].

Following [22] we divide unpaid production into categories based on sex, age-groups and employment status. For those in the working category, we average the time spent on the above activities by those working full-time and part-time. For the non-working population, we average the time of unpaid work done by the unemployed, students, homemakers and retired people.

To determine the annual time and economic value of non-market production lost, we refer to the time lost in the formal economy and its GDP valuation. In detail, we assume 250 working days (in the formal economy) and an average of 8 work hours a day, yielding 2,000 labour hours per year. Since we used per worker GDP in the non-market valuation, we aimed to express the value of the non-market losses by relating them to market losses. The following illustrative example explains our approach. Male paid workers in Belgium spent an average of 1,427 h per year on unpaid

[1] The complete list of categories used to evaluate time spent on unpaid work includes: food management except dish washing; dish washing; household upkeep except cleaning dwelling; cleaning dwelling; laundry; ironing; construction and repairs; household management and help family member; childcare, except teaching, reading and talking; teaching, reading and talking with child; informal help to other households; organisational work; participatory activities.

work (Eurostat data [41]) and this represents 71.4% of time spent on paid work (1,427 of 2,000 h). Therefore, the annual non-market output of an average worker is 71.4% of per worker GDP, additionally adjusted for lower productivity (using minimum earnings – 38.6% of an average earnings), as explained below. The respective estimates were broken down by sex, employment status, and age groups.

In practice, the use of OCA reflects the concepts of the HCA, with the following modifications. First, it accounts for losses among both the working and the non-working (unemployed and economically inactive persons). The non-working share of the population was obtained by subtracting (sex- and age-specific) employment rates from 100%. Second, we assumed that unpaid work is less productive than market activities on average. This is because most of the domestic activities are the ones that could be replaced by labour paid at rates closer to minimum earnings rather than average ones. Therefore, following [32], minimal productivity was obtained by dividing the minimum wage by the average wage in particular economies. Because there was no minimum wage legislation in six European countries in 2025 (Denmark, Italy, Austria, Finland, Sweden and Norway), the weighted (population size) mean value for the remaining countries was used for the states with no minimum wage; this mean was 43.47% of the average wage. Third, we assumed that young people aged 15–19 require care from their parents and do not perform household tasks, so we shifted the starting age of losses in the non-market economy to those aged 20–24.

### Public finance burden

In addition to productivity losses analysis, we report how these losses potentially affect public finance revenues. The labour supply decay resulting from premature mortality leads to a reduction in the total output produced. A decrease in the potential GDP results in declined income and lower consumption, which subsequently diminishes public revenues by reducing potential revenues from income and consumption taxes. This simplified analysis illustrates potential losses of public finance revenues that are attributable to decreased GDP resulting from the pandemic. For this purpose, we used Eurostat data [42] on the GDP share of the revenues for the four most important taxes (personal income tax (PIT), corporate income tax (CIT), excise tax, value added tax (VAT)) and social contributions [43, 44].

To illustrate our approach, for Belgium in 2020 (according to Eurostat data), VAT revenues constituted 6.4% of GDP and we assume that the same share of estimated productivity losses represents a rough estimate of potential VAT revenue lost. Importantly, the category of public finance burden does not represent an additional economic burden to estimated productivity losses. Rather, these potential revenues lost are a share of productivity lost within the public finance sector. The following categories of the Eurostat's main national accounts tax aggregates [42] database were used: D211 for VAT; D214A for excise tax; D51A for PIT; D51B for CIT; D61 for social contributions.

### Sensitivity and uncertainty analysis

We conducted two complementary analyses to assess the robustness of the estimates: a deterministic sensitivity analysis addressing key modelling assumptions, and an uncertainty analysis quantifying statistical uncertainty in the excess mortality inputs.

A one-way deterministic sensitivity analysis was performed to evaluate the impact of alternative economic assumptions. The following scenarios were examined: gross value added (GVA) instead of GDP; 3.5% and 0% discount rates instead of the base-scenario 5%; and uniform 0% and 2% future economic growth for all countries, instead of average EU growth rates. Additionally, we assessed the sensitivity of the results to age-group assignment by assuming that all deaths within each 5-year age group occurred either at the lower or upper bound of the interval, addressing potential bias arising from midpoint age assignment. To quantify uncertainty around the point estimates, we propagated the 95% uncertainty intervals of excess mortality estimates (as reported in [26]) through the productivity loss calculations. Productivity losses were recalculated using the lower and upper bounds of the excess death uncertainty intervals, thereby reflecting statistical uncertainty arising from the mortality estimation rather than alternative modelling assumptions.

## Results

### Productivity losses from excess and COVID-19 deaths

Total paid productivity losses from excess deaths (ED) in 2020–2023 across all 28 countries combined were €57.6 billion in the Human Capital Approach (HCA) and €3.1 billion in the Friction Cost Approach (FCA) (Table 1). Estimated unpaid productivity losses were of higher magnitude, with a combined Opportunity Cost Approach (OCAe + OCAn) total of €72.5 billion (Table 2). Productivity losses attributable to COVID-19 deaths (CD) were consistently lower across all valuation approaches (e.g. €35.0 billion for HCA), but followed the same relative ordering (Tables S1-S2).

In absolute terms, cross-country differences in total productivity losses largely reflected population size. Under both

**Table 1** Paid productivity losses from excess mortality in 28 European countries, 2020–2023: total and per capita estimates

| | 2020 | | 2021 | | 2022 | | 2023 | | 2020–2023 | |
|---|---|---|---|---|---|---|---|---|---|---|
| (2020 € PPS) | Million € | € | Million € | € | Million € | € | Million € | € | Million € | € |
| | HCA (FCA) | per capita HCA (FCA) | HCA (FCA) | per capita HCA (FCA) | HCA (FCA) | per capita HCA (FCA) | HCA (FCA) | per capita HCA (FCA) | Total HCA (FCA) | Average per capita HCA (FCA) |
| CEE | 3,966 (217) | 44.2 (2.4) | 10,914 (599) | 123.4 (6.8) | 2,947 (129) | 33.5 (1.5) | −694 (−54) | −7.9 (−0.6) | 17,134 (890) | 48.3 (2.5) |
| Bulgaria | 444 (21) | 67.6 (3.2) | 1,162 (54) | 177.8 (8.3) | 126 (9) | 19.4 (1.3) | −212 (−7) | −32.9 (−1.1) | 1,520 (77) | 58.0 (2.9) |
| Czechia | 293 (35) | 27.4 (3.2) | 1,144 (109) | 109.0 (10.4) | 370 (25) | 35.2 (2.4) | 96 (6) | 8.9 (0.5) | 1,903 (175) | 45.1 (4.1) |
| Hungary | 309 (19) | 31.9 (2.0) | 1,381 (85) | 143.1 (8.8) | 350 (19) | 36.4 (2.0) | 48 (−2) | 4.9 (−0.2) | 2,086 (121) | 54.1 (3.1) |
| Poland | 1,982 (97) | 52.2 (2.5) | 4,263 (211) | 115.0 (5.7) | 1,704 (64) | 46.2 (1.7) | −63 (−16) | −1.7 (−0.4) | 7,886 (356) | 52.9 (2.4) |
| Romania | 874 (41) | 45.2 (2.1) | 2,255 (103) | 117.4 (5.4) | 209 (3) | 11.0 (0.2) | −591 (−35) | −31.0 (−1.8) | 2,747 (112) | 35.7 (1.5) |
| Slovakia | 65 (4) | 11.8 (0.7) | 709 (37) | 129.9 (6.8) | 189 (8) | 34.7 (1.5) | 29 (0) | 5.4 (−0.1) | 992 (49) | 45.5 (2.3) |
| NE | 799 (35) | 21.0 (0.9) | 1,628 (98) | 42.6 (2.6) | 1,680 (96) | 43.7 (2.5) | 1,536 (63) | 39.5 (1.6) | 5,643 (291) | 36.7 (1.9) |
| Denmark | −2 (−2) | −0.3 (−0.4) | 5 (1) | 0.9 (0.2) | 115 (5) | 19.6 (0.9) | 80 (3) | 13.5 (0.5) | 199 (6) | 8.4 (0.3) |
| Estonia | 41 (2) | 30.6 (1.5) | 146 (8) | 109.7 (5.8) | 136 (5) | 102.1 (3.8) | 118 (3) | 86.2 (2.1) | 440 (18) | 82.1 (3.3) |
| Finland | 138 (6) | 25.0 (1.1) | 65 (9) | 11.7 (1.6) | 183 (15) | 33.0 (2.7) | 193 (12) | 34.8 (2.2) | 579 (43) | 26.1 (1.9) |
| Ireland | 187 (4) | 37.3 (0.8) | 412 (16) | 81.3 (3.1) | 333 (11) | 64.6 (2.1) | 270 (3) | 51.2 (0.6) | 1,202 (34) | 58.6 (1.7) |
| Latvia | −8 (1) | −4.5 (0.3) | 327 (21) | 172.5 (11.0) | 239 (12) | 127.7 (6.3) | 148 (7) | 78.8 (3.5) | 706 (40) | 93.6 (5.3) |
| Lithuania | 309 (15) | 110.1 (5.5) | 554 (31) | 197.1 (10.9) | 305 (15) | 108.8 (5.4) | 183 (7) | 64.2 (2.6) | 1,352 (68) | 120.0 (6.1) |
| Norway | 27 (1) | 5.0 (0.1) | −13 (3) | −2.5 (0.5) | 297 (25) | 54.8 (4.6) | 395 (19) | 72.0 (3.4) | 706 (47) | 32.3 (2.1) |
| Sweden | 107 (9) | 10.4 (0.8) | 132 (11) | 12.7 (1.1) | 71 (7) | 6.8 (0.7) | 148 (9) | 14.1 (0.8) | 459 (36) | 11.0 (0.9) |
| SE | 3,339 (163) | 24.6 (1.2) | 4,728 (231) | 35.0 (1.7) | 3,461 (149) | 25.7 (1.1) | 2,220 (70) | 16.4 (0.5) | 13,748 (612) | 25.4 (1.1) |
| Croatia | 30 (3) | 7.6 (0.7) | 229 (14) | 58.8 (3.6) | 51 (4) | 13.2 (0.9) | −15 (1) | −3.8 (0.4) | 295 (22) | 19.0 (1.4) |
| Cyprus | 18 (1) | 19.8 (1.0) | 65 (3) | 70.6 (3.0) | 13 (1) | 13.9 (0.7) | 14 (−1) | 14.8 (−0.6) | 109 (4) | 29.8 (1.0) |
| Greece | 58 (3) | 5.4 (0.3) | 586 (23) | 54.8 (2.1) | 114 (5) | 10.9 (0.4) | −111 (−7) | −10.6 (−0.7) | 647 (24) | 15.1 (0.6) |
| Italy | 1,594 (94) | 26.7 (1.6) | 2,302 (130) | 38.9 (2.2) | 1,737 (93) | 29.4 (1.6) | 1,591 (68) | 27.0 (1.1) | 7,224 (386) | 30.5 (1.6) |
| Malta | 10 (1) | 19.0 (1.3) | 4 (1) | 8.6 (1.5) | 9 (1) | 17.3 (1.4) | −15 (0) | −28.1 (−0.3) | 8 (2) | 4.2 (1.0) |
| Portugal | 278 (10) | 26.8 (0.9) | 305 (13) | 29.3 (1.3) | 245 (9) | 23.5 (0.8) | 134 (2) | 12.8 (0.2) | 962 (34) | 23.1 (0.8) |
| Slovenia | 28 (2) | 13.4 (0.8) | 72 (5) | 34.2 (2.3) | 54 (3) | 25.8 (1.2) | 32 (2) | 15.2 (0.7) | 187 (11) | 22.2 (1.3) |
| Spain | 1,323 (50) | 28.0 (1.1) | 1,165 (42) | 24.6 (0.9) | 1,238 (35) | 26.1 (0.7) | 590 (4) | 12.3 (0.1) | 4,315 (130) | 22.7 (0.7) |
| WE | 2,351 (159) | 12.4 (0.8) | 6,780 (444) | 35.8 (2.3) | 7,313 (438) | 38.5 (2.3) | 4,591 (228) | 24.1 (1.2) | 21,035 (1,269) | 27.7 (1.7) |
| Austria | 109 (10) | 12.2 (1.2) | 419 (30) | 46.9 (3.4) | 328 (27) | 36.5 (3.0) | 280 (17) | 30.7 (1.9) | 1,136 (84) | 31.6 (2.4) |
| Belgium | 325 (25) | 28.2 (2.2) | 411 (27) | 35.5 (2.3) | 394 (28) | 33.9 (2.4) | 219 (15) | 18.6 (1.3) | 1,349 (96) | 29.1 (2.1) |
| France | 637 (49) | 9.4 (0.7) | 1,404 (87) | 20.7 (1.3) | 1,994 (95) | 29.3 (1.4) | 1,060 (37) | 15.5 (0.5) | 5,095 (269) | 18.7 (1.0) |
| Germany | 796 (47) | 9.6 (0.6) | 3,640 (232) | 43.8 (2.8) | 3,759 (232) | 45.2 (2.8) | 2,376 (114) | 28.6 (1.4) | 10,572 (625) | 31.8 (1.9) |
| Luxembourg | 1 (0) | 2.1 (0.2) | −4 (0) | −6.1 (0.8) | −20 (−1) | −30.7 (−1.5) | −36 (−1) | −55.1 (−2.1) | −59 (−2) | −22.5 (−0.7) |
| Netherlands | 483 (27) | 27.7 (1.6) | 910 (67) | 52.1 (3.8) | 858 (57) | 48.8 (3.2) | 692 (46) | 38.9 (2.6) | 2,943 (197) | 41.9 (2.8) |
| Total | 10,456 (574) | 25.6 (1.3) | 24,050 (1,372) | 59.2 (3.3) | 15,401 (811) | 35.3 (1.8) | 7,654 (306) | 18.0 (0.7) | 57,560 (3,063) | 34.5 (1.8) |

Notes: HCA – human capital approach; FCA – friction cost approach; CEE – Central and Eastern Europe; NE – Northern Europe; SE – Southern Europe; WE—Western Europe; PPS – purchasing power standard. For COVID-19 results, see Table S1 in the supplementary file

**Table 2** Unpaid productivity losses from excess mortality in 28 European countries, 2020–2023: total and per capita estimates

| | 2020 | | 2021 | | 2022 | | 2023 | | 2020–2023 | |
|---|---|---|---|---|---|---|---|---|---|---|
| (2020 € PPS) | Million € | € | Million € | € | Million € | € | Million € | € | Million € | € |
| | OCAe (OCAn) | per capita OCAe (OCAn) | OCAe (OCAn) | per capita OCAe (OCAn) | OCAe (OCAn) | per capita OCAe (OCAn) | OCAe (OCAn) | per capita OCAe (OCAn) | OCAe (OCAn) | average per capita OCAe (OCAn) |
| CEE | 1,439 (4,935) | 16.0 (55.0) | 3,989 (12,021) | 45.1 (136.0) | 1,081 (2,013) | 12.3 (22.9) | −243 (−1,766) | −2.8 (−20.0) | 6,266 (17,202) | 17.7 (48.5) |
| Bulgaria | 148 (424) | 22.5 (64.6) | 397 (1,036) | 60.8 (158.7) | 46 (208) | 7.1 (32.1) | −71 (−106) | −11.0 (−16.4) | 520 (1,563) | 19.8 (59.8) |
| Czechia | 97 (335) | 9.1 (31.3) | 378 (1,010) | 36.1 (96.2) | 118 (192) | 11.3 (18.3) | 19 (−23) | 1.8 (−2.2) | 613 (1,513) | 14.5 (35.9) |
| Hungary | 96 (276) | 9.9 (28.5) | 429 (989) | 44.5 (102.5) | 108 (196) | 11.2 (20.4) | 19 (−31) | 2.0 (−3.3) | 652 (1,429) | 16.9 (37.0) |
| Poland | 753 (2,289) | 19.8 (60.3) | 1,660 (4,658) | 44.8 (125.6) | 669 (1,149) | 18.1 (31.2) | −7 (−586) | −0.2 (−16.0) | 3,074 (7,510) | 20.6 (50.3) |
| Romania | 321 (1,465) | 16.6 (75.8) | 835 (3,360) | 43.5 (175.0) | 71 (89) | 3.8 (4.7) | −209 (−976) | −11.0 (−51.2) | 1,019 (3,938) | 13.2 (51.1) |
| Slovakia | 25 (145) | 4.5 (26.7) | 289 (968) | 53.0 (177.2) | 69 (178) | 12.6 (32.8) | 5 (−43) | 1.0 (−8.0) | 388 (1,248) | 17.8 (57.2) |
| NE | 252 (417) | 6.6 (10.9) | 533 (1,011) | 13.9 (26.4) | 553 (1,042) | 14.4 (27.1) | 504 (682) | 13.0 (17.5) | 1,842 (3,153) | 12.0 (20.5) |
| Denmark | 1 (−26) | 0.2 (−4.4) | 10 (26) | 1.7 (4.4) | 43 (80) | 7.3 (13.6) | 30 (11) | 5.0 (1.9) | 84 (91) | 3.6 (3.9) |
| Estonia | 12 (14) | 8.9 (10.3) | 45 (61) | 34.0 (45.9) | 40 (36) | 30.4 (26.7) | 35 (17) | 25.5 (12.2) | 132 (127) | 24.7 (23.8) |
| Finland | 39 (70) | 7.1 (12.7) | 19 (115) | 3.5 (20.8) | 64 (239) | 11.6 (43.1) | 63 (191) | 11.3 (34.3) | 186 (616) | 8.4 (27.7) |
| Ireland | 58 (57) | 11.6 (11.5) | 123 (187) | 24.4 (36.8) | 102 (139) | 19.8 (27.0) | 76 (75) | 14.5 (14.3) | 360 (459) | 17.6 (22.4) |
| Latvia | −4 (6) | −2.0 (3.1) | 101 (172) | 53.4 (90.9) | 70 (92) | 37.4 (49.3) | 39 (46) | 20.9 (24.5) | 207 (317) | 27.4 (42.0) |
| Lithuania | 105 (178) | 37.3 (63.2) | 195 (311) | 69.3 (110.8) | 110 (169) | 39.2 (60.1) | 63 (63) | 22.1 (22.0) | 473 (721) | 42.0 (64.0) |
| Norway | 13 (4) | 2.4 (0.7) | 1 (30) | 0.1 (5.5) | 110 (205) | 20.2 (37.8) | 148 (184) | 27.0 (33.6) | 271 (423) | 12.4 (19.4) |
| Sweden | 28 (113) | 2.7 (11.0) | 38 (109) | 3.7 (10.5) | 13 (82) | 1.3 (7.9) | 50 (95) | 4.7 (9.0) | 129 (400) | 3.1 (9.6) |
| SE | 1,230 (5,356) | 9.1 (39.5) | 1,724 (6,134) | 12.8 (45.4) | 1,272 (3,909) | 9.4 (29.0) | 788 (1,591) | 5.8 (11.7) | 5,013 (16,989) | 9.3 (31.4) |
| Croatia | 13 (157) | 3.3 (39.8) | 92 (462) | 23.7 (118.8) | 19 (139) | 4.9 (36.1) | −4 (43) | −1.0 (11.2) | 120 (802) | 7.7 (51.5) |
| Cyprus | 6 (10) | 6.7 (11.5) | 22 (40) | 23.6 (43.5) | 4 (14) | 4.7 (14.7) | 3 (−8) | 3.7 (−8.9) | 35 (55) | 9.7 (15.2) |
| Greece | 25 (169) | 2.3 (15.8) | 210 (741) | 19.6 (69.4) | 42 (219) | 4.0 (21.0) | −35 (−82) | −3.3 (−7.8) | 242 (1,047) | 5.7 (24.6) |
| Italy | 538 (2,791) | 9.0 (46.8) | 793 (2,971) | 13.4 (50.1) | 594 (2,049) | 10.1 (34.7) | 544 (1,418) | 9.2 (24.0) | 2,468 (9,229) | 10.4 (38.9) |
| Malta | 1 (6) | 2.6 (12.4) | 0 (10) | −1.0 (20.1) | 0 (8) | 0.1 (16.2) | −7 (−7) | −13.3 (−13.1) | −6 (18) | −2.9 (8.9) |
| Portugal | 106 (221) | 10.2 (21.3) | 119 (309) | 11.5 (29.7) | 91 (184) | 8.8 (17.6) | 41 (50) | 3.9 (4.7) | 358 (763) | 8.6 (18.3) |
| Slovenia | 13 (31) | 6.4 (15.0) | 32 (101) | 15.1 (48.0) | 27 (32) | 12.8 (15.4) | 15 (−19) | 7.0 (−9.1) | 87 (146) | 10.3 (17.3) |
| Spain | 527 (1,970) | 11.1 (41.6) | 458 (1,500) | 9.7 (31.6) | 494 (1,263) | 10.4 (26.6) | 230 (197) | 4.8 (4.1) | 1,710 (4,929) | 9.0 (26.0) |
| WE | 691 (2,707) | 3.7 (14.3) | 2,071 (5,574) | 10.9 (29.4) | 2,330 (5,151) | 12.3 (27.1) | 1,393 (2,112) | 7.3 (11.1) | 6,485 (15,545) | 8.5 (20.5) |
| Austria | 33 (190) | 3.8 (21.4) | 134 (449) | 15.0 (50.2) | 106 (352) | 11.8 (39.2) | 89 (179) | 9.8 (19.7) | 362 (1,171) | 10.1 (32.6) |
| Belgium | 99 (500) | 8.6 (43.4) | 129 (380) | 11.2 (32.8) | 125 (384) | 10.7 (33.0) | 71 (135) | 6.1 (11.5) | 425 (1,398) | 9.2 (30.2) |
| France | 223 (1,353) | 3.3 (20.1) | 491 (2,049) | 7.2 (30.2) | 740 (1,927) | 10.9 (28.3) | 371 (506) | 5.4 (7.4) | 1,824 (5,835) | 6.7 (21.5) |
| Germany | 199 (375) | 2.4 (4.5) | 1,039 (2,084) | 12.5 (25.1) | 1,105 (2,047) | 13.3 (24.6) | 672 (956) | 8.1 (11.5) | 3,015 (5,462) | 9.1 (16.4) |
| Luxembourg | 2 (−3) | 2.8 (−4.3) | 2 (−4) | 3.5 (−5.9) | −6 (−20) | −9.8 (−30.7) | −9 (−63) | −13.6 (−95.7) | −11 (−89) | −4.2 (−34.1) |
| Netherlands | 135 (291) | 7.7 (16.7) | 276 (617) | 15.8 (35.3) | 260 (462) | 14.8 (26.2) | 199 (399) | 11.2 (22.4) | 869 (1,768) | 12.4 (25.2) |
| Total | 3,612 (13,414) | 8.8 (29.9) | 8,316 (24,740) | 20.7 (59.3) | 5,236 (12,115) | 12.1 (26.5) | 2,442 (2,619) | 5.8 (5.1) | 19,606 (52,889) | 11.9 (30.2) |

Notes: OCAe – opportunity cost approach for the employed; OCAn – opportunity cost approach for the non-employed (unemployed, students, homemakers and retired persons); CEE – Central and Eastern Europe; NE – Northern Europe; SE – Southern Europe; WE—Western Europe; PPS – purchasing power standard. For COVID-19 results, see Table S2 in the supplementary file

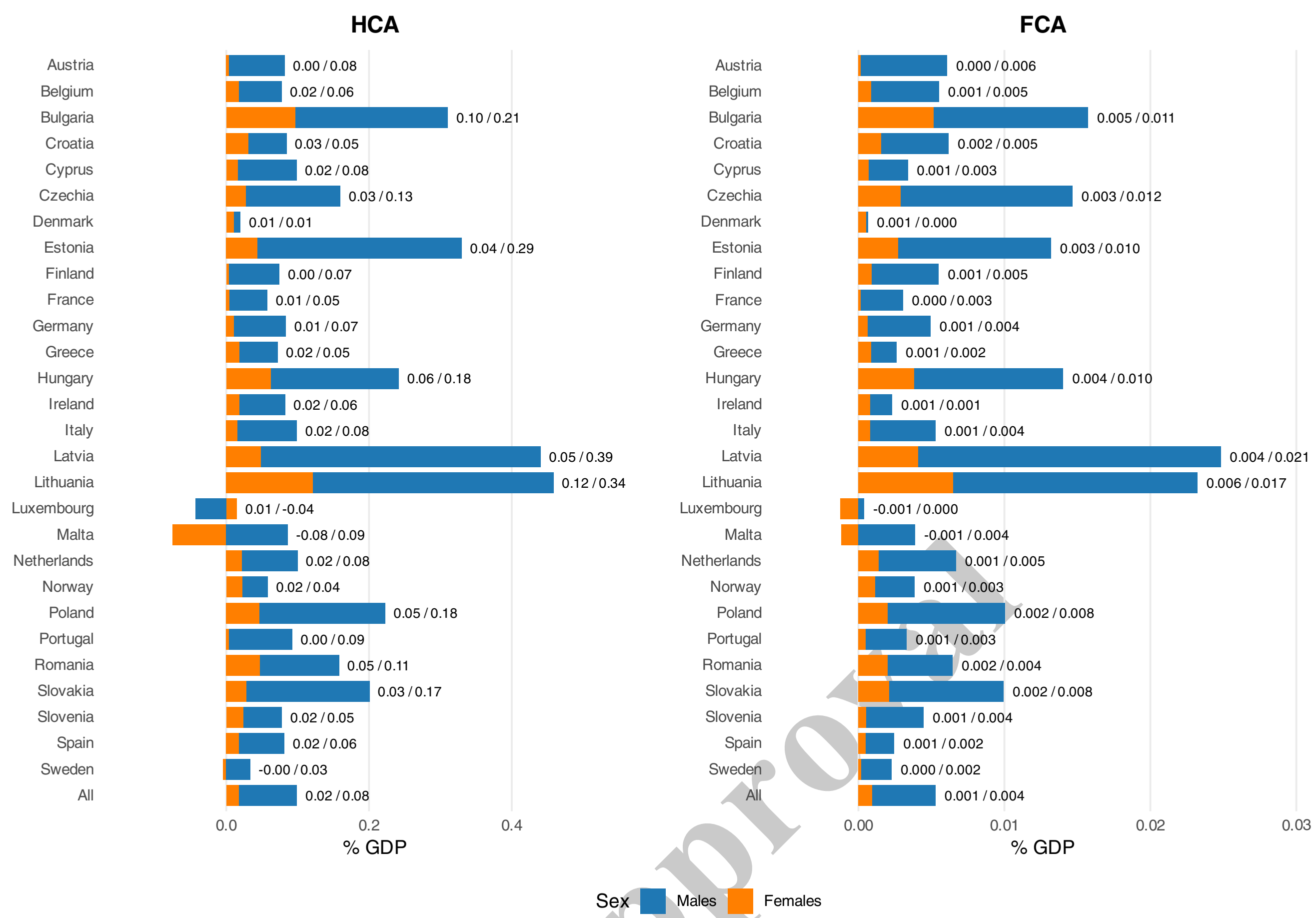


**Fig. 1** Paid productivity losses from excess deaths in 28 European countries, 2020–2023: share of gross domestic product (GDP) lost



HCA and FCA, the highest paid losses were observed in the largest countries, notably Germany, Poland, and Italy, while unpaid losses were relatively more pronounced in Italy and Poland (Tables 1 & 2, Table S1 & Table S2). These patterns were consistent for ED and CD.

When expressed relative to the economic size, paid productivity losses under HCA averaged 0.10% of GDP for excess deaths (ED), (range: –0.03% to 0.46%), and 0.06% for COVID-19 deaths (CD) (0.01% to 0.28%) (Fig. 1; Fig. S1). Under FCA, average losses were markedly smaller (0.005% for ED and 0.004% for CD). For estimates based on ED, we identified negative losses[2] for low-populated countries. A similar pattern was observed for unpaid productivity; both OCAe and OCAn displayed ranges spanning negative to positive GDP shares (in ED, up to 0.16% in OCAe and 0.32% in OCAn), with losses from the non-employed population generally exceeding losses among the employed (Fig. 2; Fig. S2).

Across all valuation methods, relative losses varied substantially across countries but showed a consistent geographic gradient. Higher proportional burden was concentrated in Central and Eastern Europe (CEE), and in three Northern European (NE) states (Estonia, Latvia, and Lithuania), whereas Western (WE) and Nordic countries generally experienced smaller, and in some cases negative losses (among low-populated countries such as Malta and Luxembourg).

## Time distribution of productivity losses

Our results show marked temporal variation across countries. For ED, losses peaked in 2021 in Central and Eastern Europe (CEE) and Southern Europe (SE), whereas Western European (WE) countries experienced their highest losses predominantly in 2022. Northern Europe (NE) showed a more even distribution of losses across 2021–2023. This time-region pattern was consistent across valuation methods used, but only for excess deaths. At the country level, several CEE countries experienced a pronounced concentration of losses in 2021, followed by a sharp decline by

[2] Negative productivity losses result from negative excess mortality, i.e. a situation when lower than expected mortality was observed in some periods/countries. Such results should not be interpreted as economic gains, but we report them for transparency.

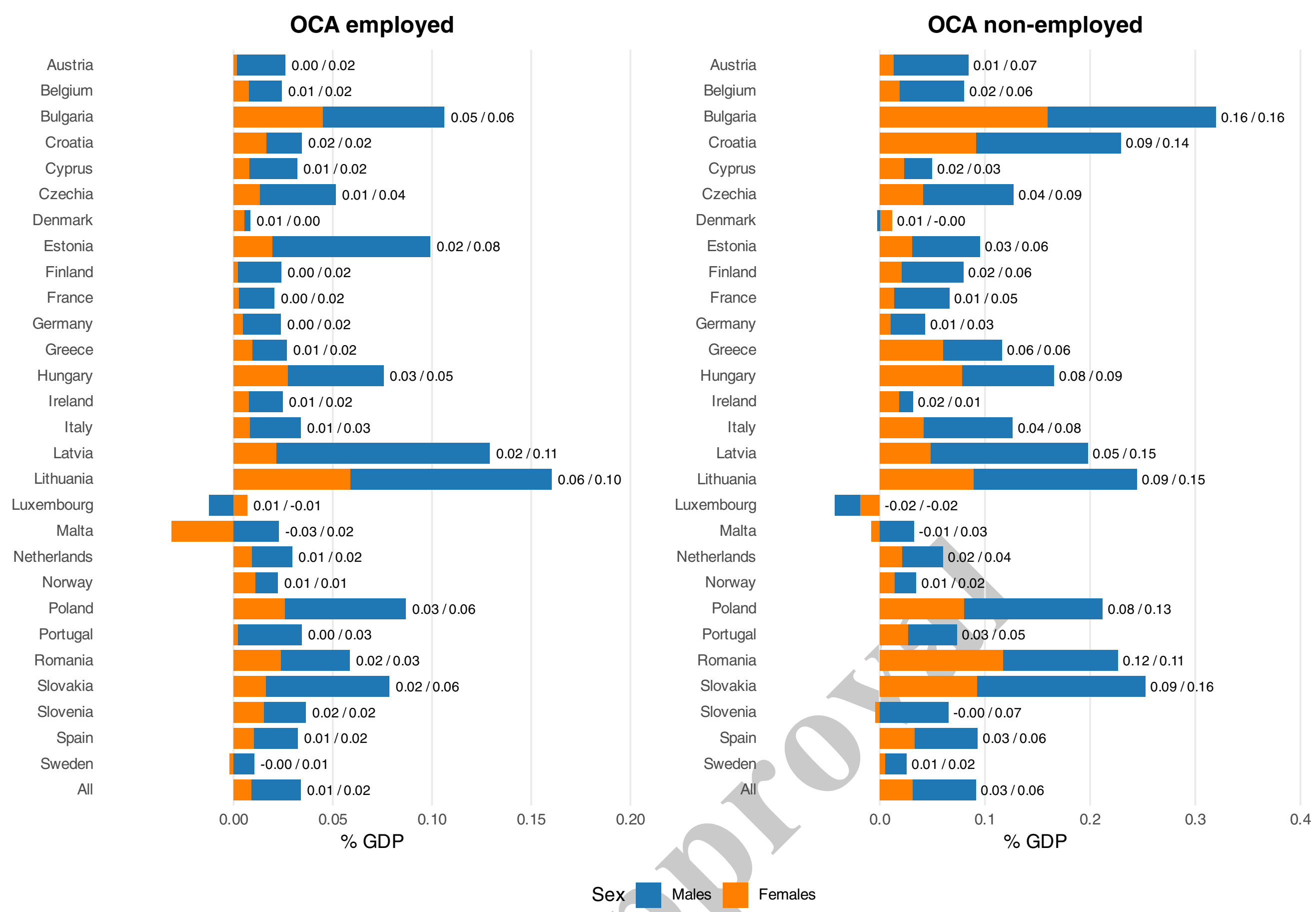


**Fig. 2** Unpaid productivity losses from excess mortality in 28 European countries, 2020–2023: share of gross domestic product (GDP) lost

2023, in some cases reaching negative values, while parts of Northern Europe (Finland, Norway and Sweden) exhibited a delayed peak, with the greatest burden in 2023. In contrast, in countries such as Spain and Italy, productivity losses were distributed more evenly across years (Tables 1, 2). In contrast, for COVID-19 deaths, the burden of productivity losses was the highest in 2021 for all regions (data for 2023 not available for most countries) (Table S1 and Table S2).

## Sex- and age-specific productivity losses

Sex-specific figures reveal a notable disparity, with men accounting for the majority of productivity losses across all valuation approaches and mortality measures. Under both HCA and FCA, male ED made up 82% of losses and 76% in CD. For unpaid losses, sex differences were smaller but still notable: among the employed (OCAe), males contributed 74% of losses for ED (Fig. 3) and 66% for CD (Fig. S3); in non-employed (OCAn), the sex distribution was more proportional, but still male shares were higher (Fig. 3 and Fig S3). These patterns were also reflected in GDP-related terms: across all methods, men accounted for the larger share of GDP losses, with women contributing a markedly smaller proportion (Fig. 1; Fig. 2).

Age-specific patterns differed by valuation approach. Under HCA and OCAe, productivity losses were concentrated in the core working-age population (40–59 years), which accounted for the majority of losses for both ED and CD (Fig. 3; Fig. S3). FCA displayed a similar profile but with a greater relative contribution from older working ages (60–74 years). In contrast, unpaid productivity losses among the non-employed (OCAn) were dominated by older age groups, with individuals aged 60–74 accounting for the largest share of losses for both ED and CD.

## Regional differences in productivity losses

From an absolute perspective, regional differences in productivity losses largely reflected the distribution of population and economic activity. Western European countries accounted for the largest absolute paid productivity losses under HCA (€21.0 billion) and FCA for excess deaths (€1.3 billion), and under FCA for COVID-19 deaths (€0.8 billion), followed by Central and Eastern Europe, Southern Europe, and Northern Europe (Tables 1 & S1). In contrast,

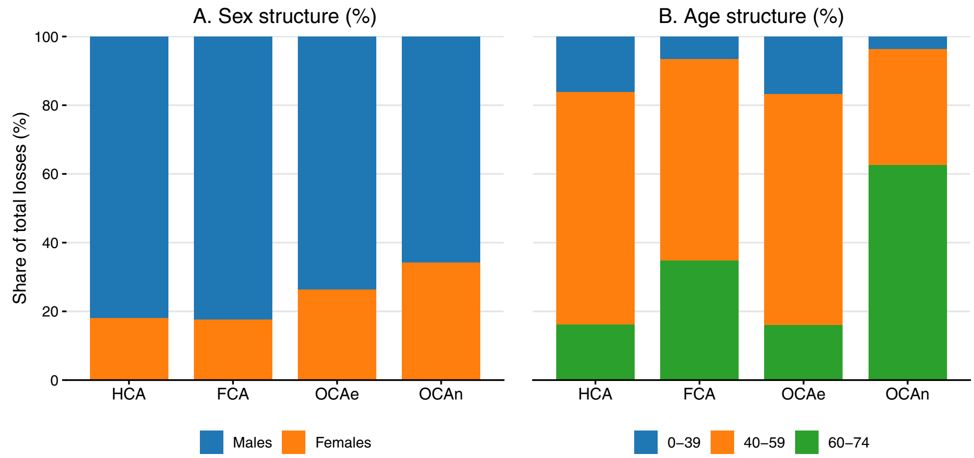


**Fig. 3** Sex- and age-specific breakdowns of productivity losses from excess mortality in 28 European countries

under HCA for CD and for unpaid productivity losses estimated using OCAe and OCAn, CEE countries consistently exhibited the highest absolute losses (Tables 1–2, S1–S2). Across all approaches and mortality measures, Northern European countries, apart from three Baltic states (Lithuania, Latvia, and Estonia), recorded the lowest absolute productivity losses.

When expressed relative to economic size, a markedly different pattern emerged. CEE and the three mentioned Baltic states countries consistently experienced the highest productivity losses as a share of GDP across all valuation approaches and for both ED and CD (Fig. 1; Fig. 2; Fig. S1; Fig. S2). By contrast, Nordic and Western European countries were generally among those with the lowest relative burdens, regardless of the method or mortality measure used.

## Per capita productivity losses

Per capita productivity losses exhibited pronounced cross-country variation and a highly consistent ranking across valuation approaches. The highest per capita losses, both for ED and CD, were concentrated in CEE and three Baltic countries, regardless of whether paid or unpaid productivity losses were considered (Tables 1, 2; Tables S1–S2). For example, under HCA for ED, per capita losses exceeded €80 in Lithuania, Latvia and Estonia, compared with values below €20 in several Nordic (Denmark and Sweden) and SE countries (Greece, Malta, Croatia) (Table 1). Similarly, unpaid losses among the non-employed (OCAn) reached nearly €65 per capita in Lithuania and €60 in Bulgaria for ED, while remaining negative in countries such as Luxembourg (Table 2).

Nordic countries and small economies consistently exhibited the lowest per capita losses. Norway, Finland, Sweden, Denmark, Luxembourg, and Malta were among the countries most frequently recording very low—and in some cases negative—per capita productivity losses across valuation methods and mortality measures.

## Public finance burden

The public finance burden attributable to excess deaths, aggregated across all countries and years, amounted to €19.7 billion under the Human Capital Approach (HCA) and €1.1 billion under the Friction Cost Approach (FCA) (Table 3). In absolute terms, the largest fiscal burden was observed in WE, accounting for approximately €7.9 billion under HCA and €0.5 billion under FCA, followed by CEE, SE, and NE. For COVID-19 deaths used as the mortality measure, the total public revenue burden was lower (€11.9 billion for HCA and €0.7 billion for FCA; Table S5), but the regional ranking remained unchanged, mirroring that observed for excess deaths.

## Sensitivity and uncertainty analysis

The one-way deterministic sensitivity analysis indicates that productivity loss estimates are sensitive to selected modelling assumptions. Table 4, Panel A reports population-weighted average percentage changes for all deterministic sensitivity scenarios based on excess deaths (ED), and Table S6 for COVID-19 deaths (CD). Tables S7–S10 present detailed country-specific base-scenario losses and their variation for ED and CD.

For FCA, assessed only for the alternative productivity measure, replacing GDP with gross value added reduced paid productivity losses by 9.6% for ED (Table 4) and 9.7% for CD (Table S6). Under HCA, the largest deviations from the base scenario were observed for the discount rate variation. Setting the discount rate to 0% increased losses by 43.5% for ED and 46.0% for CD, while a discount rate of 3.5% resulted in increases

**Table 3** Public finance burden from excess mortality in 28 European countries, 2020–2023

| | Share of revenues from taxes and social insurance contributions as a proportion of GDP* (2020–2023 average) | Public finance revenue losses due to excess mortality (2020–2023, total in million €) | |
|---|---|---|---|
| | | HCA | FCA |
| CEE | - | 5,241 | 274 |
| Bulgaria | 27.2 | 426 | 21 |
| Czechia | 32.0 | 609 | 56 |
| Hungary | 28.7 | 592 | 34 |
| Poland | 32.3 | 2,598 | 118 |
| Romania | 25.0 | 688 | 28 |
| Slovakia | 32.9 | 327 | 16 |
| NE | - | 1,708 | 94 |
| Denmark | 41.0 | 78 | 2 |
| Estonia | 28.0 | 123 | 5 |
| Finland | 39.4 | 228 | 17 |
| Ireland | 17.9 | 216 | 6 |
| Latvia | 30.6 | 216 | 12 |
| Lithuania | 30.9 | 418 | 21 |
| Norway | 39.1 | 283 | 19 |
| Sweden | 31.7 | 145 | 11 |
| SE | - | 4,781 | 214 |
| Croatia | 34.1 | 100 | 7 |
| Cyprus | 32.5 | 35 | 1 |
| Greece | 34.4 | 225 | 8 |
| Italy | 35.9 | 2,591 | 138 |
| Malta | 23.8 | 2 | 0 |
| Portugal | 33.0 | 317 | 11 |
| Slovenia | 35.0 | 66 | 4 |
| Spain | 33.5 | 1,445 | 44 |
| WE | - | 7,940 | 479 |
| Austria | 38.0 | 433 | 32 |
| Belgium | 39.3 | 530 | 38 |
| France | 38.9 | 1,986 | 105 |
| Germany | 37.7 | 3,999 | 237 |
| Luxembourg | 33.9 | −20 | −1 |
| Netherlands | 34.5 | 1,013 | 68 |
| Total | - | 19,670 | 1,061 |

Notes: * – sum of Value added type taxes (VAT), Excise duties and consumption taxes, Taxes on individual or household income, Taxes on the income or profits of corporations, Net social contributions. HCA – human capital approach; FCA – friction cost approach; CEE – Central and Eastern Europe; NE – Northern Europe; SE – Southern Europe; WE—Western Europe. For COVID-19 results, see Table S5 in the supplementary file



of 10.8% for ED and 10.3% for CD. Alternative assumptions regarding future economic growth led to minor changes, with losses differing from the base case by −7.5% to 4.6% for ED and −5.5% to 3.9% for CD, depending on the scenario. For unpaid losses, the variations were usually slightly higher than those in HCA (Table 4 and Table S6).

Sensitivity to age-group assignment was modest. Assuming that all deaths within each 5-year age interval occurred at either the lower or upper bound of the interval resulted in changes of approximately ± 16–19% for ED and slightly above 20% for CD (Table 4 and Table S6).

Uncertainty arising from excess mortality estimation is summarised in Table 4, Panel B, which reports percentage deviations of aggregated productivity losses across all countries relative to the base-case estimate. At the aggregate level, uncertainty ranged ± 90.9% for HCA, ± 75.3% for FCA, ± 93.7% for OCAe, and ± 62.2% for OCAn (Table 4), reflecting large uncertainty around total productivity losses in all countries combined. Such aggregation was adopted to avoid unstable and potentially misleading percentage deviations at the country level arising from offsetting positive and negative excess deaths, particularly in low-population countries; further details are provided in the Notes to Table 4.

**Table 4** Summary of deterministic sensitivity and uncertainty analysis of productivity losses from excess mortality in 28 European countries, 2020–2023

Panel A. Deterministic sensitivity analysis (assumption-based scenarios)

| | Population-weighted average change from BS [%] | | | |
|---|---|---|---|---|
| | HCA | FCA | OCA employed | OCA non-employed |
| Discount rate (BS = 5%): | | | | |
| 3.5% | 10.8 | n.a | 11.2 | 12.9 |
| 0% | 43.5 | n.a | 47.0 | 59.6 |
| Productivity measure (BS = gross domestic product): | | | | |
| Gross value added | −9.8 | −10.6 | −9.8 | −9.8 |
| Future economic growth (BS = average for EU countries): | | | | |
| 0% for all the countries | −6.4 | n.a | −6.6 | −7.5 |
| 2% for all the countries | 4.2 | n.a | 4.4 | 4.6 |
| Age range (BS = each death occurs at the midpoint of an age-group): | | | | |
| Lower bound of an age-group | 16.2 | n.a | 16.3 | 17.3 |
| Upper bound of an age-group | −17.5 | n.a | −17.6 | −18.8 |

Panel B. Uncertainty analysis (propagation of excess mortality estimation uncertainty into productivity losses)

| | Percentage deviation of aggregated country-level losses from base-case estimate [%] | | | |
|---|---|---|---|---|
| Excess mortality estimation uncertainty (BS = point estimate): | | | | |
| Lower 95% CI | −90.9 | −75.3 | −93.7 | −62.2 |
| Upper 95% CI | 90.9 | 75.3 | 93.7 | 62.2 |

Notes: Panel A reports population-weighted average percentage changes across countries under alternative modelling assumptions (deterministic sensitivity analysis). Panel B reports percentage deviations of aggregated productivity losses across all countries from the base-case estimate, obtained by propagating the 95% uncertainty intervals of excess mortality estimates. Because base-case productivity losses are close to zero in some countries, as positive and negative excess deaths offset each other over time, percentage deviations derived from uncertainty bounds can become extremely large, change sign, and cancel out when averaged. To avoid misleading summaries driven by this ratio instability, productivity losses are first aggregated across all countries, and percentage deviations are then computed relative to the aggregated base-case estimate. Accordingly, Panel A summarises population-weighted sensitivity to modelling assumptions, while Panel B quantifies uncertainty around total losses; percentage changes across panels are therefore not comparable. Detailed country-specific results are shown in Tables S7-S8 in the Supplementary File

BS – base scenario; HCA – human capital approach; FCA – friction cost approach; OCA employed – opportunity cost approach for employed; OCA non-employed – opportunity cost approach for non-employed (unemployed persons, students, homemakers and retired); n.a. – not applicable. For COVID-19 results, see Table S6 in the supplementary file



## Discussion

Our cross-country analysis of productivity losses attributable to the COVID-19-related mortality in 28 European countries provides new evidence on the economic burden of the recent health crisis. Applying a four-year period (2020–2023), our study analyses both the acute pandemic and the post-pandemic endemic phases, which have rarely been examined jointly in productivity loss studies. We also contribute to the literature by applying a range of loss estimation methods that account for both paid and unpaid productivity losses. For the paid losses, we used alternatives of the human capital approach and the friction cost approach, the latter rarely applied in population-level studies on pandemic-related mortality. Additionally, we distinguished between losses from COVID-19 deaths and excess deaths. The latter approach is rare in productivity loss estimation [11]; yet, it deserves more attention in assessing the true burden of the pandemic. Epidemiological literature has placed more emphasis on excess deaths rather than deaths attributable directly to COVID-19 [16, 17, 45], and economic studies would benefit from following this approach.

### Productivity losses differences across methodological approaches

Our results reveal that the COVID-19 pandemic caused a notable economic burden in terms of productivity losses across Europe. Paid productivity losses from excess deaths in 2020–2023 were €57.6 billion under the HCA and €3.1 billion under the FCA. This disparity between the two methods is expected, given their theoretical differences. The FCA, which is based on a friction period [30], reflects labour substitution and market adjustments, while the HCA assigns the whole potential future income lost up to retirement, reflecting the maximum value of production uncompleted [9]. Therefore, the HCA/FCA ratio of 18.8 for excess deaths (range across countries: 4.0–35.4) and 16.5 for COVID-19 deaths (range: 10.2–22.3) is not surprising; a review [21] identified a respective ratio of as much as 72 for a study on coronary heart disease, and another study identified a ratio of 34.4 in cancer [46].

When it comes to FCA estimates, we note that the country- and time-specific friction periods used were derived from pre-pandemic models [40], as no validated estimates specific to the COVID-19 context were found. Importantly, although the pandemic temporarily affected labour market mechanisms in Europe, these disruptions were neither severe nor long-lasting [47]. Consequently, our FCA approach is likely to yield conservative estimates of productivity losses, since pandemic-related labour market disruptions would rather lengthen, not shorten, worker replacement periods.

Interestingly, unpaid losses, resulting from non-market activities, such as housekeeping and volunteering, generated a higher economic burden (€72.5 billion) than those from paid productivity losses (€57.6 billion under the HCA) across all the countries and years combined. There are no COVID-19-based studies to compare this proportion; however, estimates from cancer-related mortality also prove that unpaid losses are an important contributor to overall burden. European estimates from 2018 cancer mortality identified the share of unpaid losses as 49% of the total [22], while the respective proportion in our study was 55.7% of the sum of HCA and OCA for excess deaths and 61.6% for COVID-19 deaths. The higher proportion of unpaid losses in our study, compared to cancer, plausibly results from sex and age differences in mortality between these diseases and dissimilar methods. Yet, we shall note that for some countries, paid losses were larger than the unpaid ones, particularly in the excess mortality framework. This was true for most NE states, Germany and the Netherlands, all characterised by high employment rates and long economic activity. On the other hand, for countries such as Italy, Spain, Poland and Romania, the opposite was true, with unpaid losses disproportionately high.

Additionally, 73% of the unpaid losses in excess mortality (78% in COVID-19 mortality) resulted from deaths among those not active in the labour market. As this group consists largely of older adults, the figures highlight that the elderly, who often contribute more to unpaid production, were at high risk of mortality during the pandemic. Their unpaid but economically significant contribution, which was lost during the COVID-19 mortality surge, should therefore be emphasised in assessing the real economic burden of the virus. To date, productivity loss studies have mostly omitted the unpaid losses category, and our study proves that their magnitude is crucial, underlining the importance of considering both paid and unpaid labour in health economic assessments.

Importantly, for the excess mortality estimates, negative or zero productivity losses were observed in a small number of country-sex strata, reflecting negative or null excess mortality. Such results should be interpreted as the absence of an excess mortality burden rather than as economic gains; however, we reported negative values for transparency.

Finally, the proportion of COVID-19 mortality losses in excess mortality losses in all countries and years was 61% under HCA, 70% under FCA and 78% in unpaid losses. Again, these shares vary across countries; e.g. with HCA, from 16% in Estonia to 150% in Greece. These differences reflect several factors, including varying testing capacities across countries, but also the ability of health systems to tackle the health crisis and populations' vulnerability, among others [48, 49]. In general, higher excess mortality losses than COVID-19 mortality losses reflect what we know from the burden of disease studies during the pandemic. Excess mortality captures both direct COVID-19 deaths and indirect mortality attributable to the crisis – from delayed care, health system strains, and behavioural responses – offering a more comprehensive measure of the pandemic's mortality impact than cause-specific data alone [16, 45], and this similarly applies to economic studies.

## Comparison to previous studies

There is no direct way to compare previous estimates to our findings, since no study used a comparable range of methodological approaches. Our recent systematic review [11] analysed 38 studies on productivity losses, but this evidence is only partially comparable to the present figures. Using HCA, time-normalised productivity losses from excess mortality in eight EU countries until May 2020 (original study [14]; time-normalised data [11]) ranged from 0% of GDP in Germany to 0.53% in Spain. For other studies that used different methodological approaches and time frames, these time-normalised losses were 0.05% of GDP lost in Germany and 2.1% in Spain [11]. Yet, these last results from Germany refer to a longer period (until 8 Nov 2020) than the ones from Spain (19 Apr 2020); illustrating that loss estimates depend not only on mortality burden but also on the period analysed. To compare these figures with our estimates, productivity losses in Germany across four years constituted 0.08% of GDP under HCA and 0.06% of GDP in unpaid losses, and respective figures for Spain were 0.08% and 0.12%. This relatively lower variability of our estimates suggests that long-term analysis is crucial because pandemic waves struck countries at different times, and using short time frames may obscure the overall picture. Our long-term approach reduces the effects of individual pandemic waves that could otherwise inflate or deflate estimates, depending on whether the period covered included them.

### Cross-country and temporal variation in productivity losses

In absolute values, the highest productivity losses were identified in the most populous countries – Germany (€10.6 billion, HCA estimates across the whole period), Poland (€7.9 billion), Italy (€7.2 billion), France (€5.1 billion) and Spain (€4.3 billion). This hierarchy is consistent regardless of the method and mortality measure used. However, in relative terms, the burden shifts towards CEE countries and, even more, to the three Baltic states – Lithuania, Latvia and Estonia. The greatest paid productivity losses were identified in Lithuania (0.46% of GDP in HCA) and Latvia (0.025% in FCA), followed by Estonia and CEE states (refers to both HCA and FCA). A similar pattern applies to unpaid losses. This clearly reflects the higher mortality rates during the pandemic in the CEE region and the three Baltic states. Epidemiological studies [45, 50] consistently report that total excess mortality rates from 2020 to 2023 in CEE countries exceeded those of other European subregions. This higher vulnerability of Eastern European states might arise from lower health system resilience [51], lower vaccination uptake [52], socioeconomic factors (lower GDP, higher poverty rates and inequalities) [45], and a population health profile, such as a higher prevalence of chronic diseases [53].

The pattern of productivity losses across regions highlights how the pandemic's mortality evolved heterogeneously across Europe. Under the excess mortality approach, losses peaked earlier in CEE and SE (2021), later in WE (2022), and last in NE (2023), consistent across paid (both HCA and FCA), and unpaid losses. This staging likely reflects the interaction of different trajectories of the spread of COVID-19 [54], vaccination coverage [55], and strain on health systems [56–58]. The sharp peak of losses in 2021 in Lithuania, Latvia, Poland, and Romania, followed by significant declines in 2023, contrasts with Finland, Norway, and Sweden, where the productivity losses were the highest in 2023 – consistent with a delayed excess mortality impact. In comparison, Spain and Italy show a more even, multi-year spread of losses, illustrating more dispersed waves. Importantly, when considering deaths directly attributed to COVID-19, losses peak in 2021 for all regions (with limited 2023 data), narrowing the apparent timing differences. This divergence shows that excess mortality, by capturing both direct and indirect effects, provides a more accurate measure of the pandemic's true burden in both epidemiological and economic terms.

### Sex and age patterns in productivity losses

Across methods and both mortality measures, men account for the majority of losses. This is consistent with evidence showing that men are at greater risk of mortality, either from COVID-19 or most other conditions [59, 60]. The sex disproportion in excess mortality is therefore not surprising and is not exclusive to the COVID-19 pandemic, but is a general characteristic of any excess mortality [61]. These epidemiological differences, combined with labour market characteristics (higher male employment and earnings in most EU countries [62]), result in larger paid productivity losses for men.

Age profiles in our results differ by method, reflecting what theory predicts. HCA and unpaid losses among the employed concentrate in prime working ages (40–59), where remaining work years, participation, and productivity are highest. FCA slightly flattens the profile because replacement reduces long-term burden; therefore, losses among the elderly are substantial here (35% of the total, compared to 16% in HCA and OCAe). Unpaid losses in non-employed (OCAn) shifts focus to older working ages (60–74) and females, consistent with higher mortality among older adults [63] and the greater participation of women in unpaid work [64]. Our results in terms of age and sex distribution are in line with the systematic review (11), claiming that losses concentrated among the middle-aged and that three-quarters of mortality losses were due to men's deaths.

### Public finance burden – potential revenues lost

Estimates indicate a significant burden on public finance related to pandemic mortality, with its level depending on both the mortality measure and the valuation methodology. The sum of potential public revenues (taxes and social contributions) lost due to decreased GDP resulting from excess mortality was €19.7 billion under HCA and €1.1 billion under FCA. Again, the difference between HCA and FCA is evident; HCA considers lost future income, whereas FCA is limited to the short-term replacement period. The regional hierarchy remains consistent (WE > CEE > SE > NE), reflecting differences in tax rates and mortality rates. From a fiscal policy perspective, HCA results highlight the importance of a long-term view – preventing deaths among working-age populations preserves future tax revenues.

### Stability of estimates

The robustness of the estimated productivity losses was assessed using two complementary approaches: a deterministic sensitivity analysis addressing key modelling assumptions, and an uncertainty analysis propagating statistical uncertainty from excess mortality estimates.

In the deterministic sensitivity analysis, results were most sensitive to assumptions regarding the discount rate. Setting the discount rate to 0% resulted in substantially higher losses compared to the base scenario, with increases ranging 43.5–59.6% in ED. This reflects the fact that mortality-related productivity losses accumulate in future periods and are therefore strongly affected by discounting. In contrast, alternative assumptions regarding productivity measure used, future economic growth, and death assignment within 5-year age groups produced modest changes and did not affect the substantive conclusions of the analysis.

In low-population countries, sensitivity analyses based on excess deaths revealed very large relative deviations under some scenarios; in Malta and Luxembourg, percentage changes exceeded several hundred percent under the no discounting scenario. These extreme proportional changes arise when positive and negative excess deaths partially offset each other over time, resulting in very low productivity loss estimates in the base scenario. In such cases, even small absolute changes can translate into large relative differences when alternative assumptions are applied. This instability at the country level underscores the need to interpret estimates for small populations with caution.

Notably, accounting for uncertainty from excess mortality estimates yields wide uncertainty ranges in productivity losses, with aggregated deviations exceeding ± 90% in some valuation methods. This reflects the fact that excess deaths were estimated using sex- and age-stratified regression models based on small numbers of observations, resulting in wide uncertainty intervals that are subsequently propagated into the productivity loss estimates. Again, this issue is particularly relevant for small countries, where excess mortality models are inherently less stable. At the same time, these uncertainty ranges should be interpreted as extreme scenarios, as they reflect situations in which all countries simultaneously experience excess mortality corresponding to the lower or upper bounds of the uncertainty intervals. Finally, the excess mortality estimates underlying our analysis are broadly consistent with findings from other cross-country studies [26, 27], supporting the plausibility of productivity loss results based on excess mortality base-case scenario.

## Policy implications

From a policy perspective, the productivity losses estimated here might be interpreted as a part of the broader macroeconomic impact of the pandemic. Eurostat figures show a 5.6-percent decline in GDP in 2020 in EU-27 countries, with respective figures of 9–10 percent in SE countries [65]. This recession was driven by multiple channels, including containment measures, demand contractions, supply-chain disruptions, and fiscal responses [66]. In contrast, our estimates capture a specific and policy-relevant component of this shock, i.e. losses related to reduced productivity due to pandemic-related mortality, and thus represent only a part of total pandemic-related GDP effects (€10.5 billion and 0.08% of GDP lost in 2020 for HCM based on excess deaths).

Our results nevertheless have important policy implications for assessing the pandemic's economic burden. First, although COVID-19 most severely affected the elderly, mortality among the middle-aged generated the greatest productivity losses. This is not surprising because this group is the most productive and has the highest employment rates. As those in their 40 s and 50 s combine the highest economic contribution with increasing chronic-disease risk, disruptions to routine care during health crises translate directly to substantial productivity losses. Ensuring continuity of routine care (e.g. cardiovascular, oncology services) is therefore not only a clinical priority but also an economic one.

Second, our approach that extends losses beyond retirement age (up to age 75) shows that economic studies should account for the retirement-aged population that is economically active, in terms of both paid and unpaid productivity. Substantial losses among those over 60, combined with rising employment rates in this group and population ageing in Europe, underscore the importance of investments in the elderly's health to secure future economic growth.

Third, the magnitude of unpaid losses highlights the significant economic impacts of household production, caregiving, and volunteer activities. In our study, the unpaid losses exceeded those of paid work, despite using conservative assumptions (minimum productivity for calculating unpaid work instead of the average productivity applied to paid work). Eventually, the concentration of losses among men, particular countries, and in specific age groups interacts with regional socio-economic gradients. Where excess mortality and economic vulnerability converged (CEE and the three Baltic states), the proportional productivity burden was greatest. This calls for targeted investment in preventive services, occupational health, and surge capacity within the health systems of the most affected regions.

## Limitations

The following caveats apply to our study. Our estimates only report productivity losses arising from deaths attributable to the pandemic, while losses from COVID-19 morbidity (absenteeism, presenteeism, caregiving) might be even higher than from mortality [4, 67]. Also, the methods used for productivity losses estimation are not perfect. Each method we employed, either the human capital or friction cost approaches for paid losses and the opportunity cost approach for unpaid losses, has its own drawbacks [9, 21]. We opted for analysing a wide range of estimation approaches and provided a comprehensive set of estimates, allowing readers to judge which method is most useful for their purpose. Moreover, there are concerns regarding the quality of mortality data, either excess mortality or COVID-19 mortality. For the former, there are numerous approaches used for identifying the number of excess deaths and no gold standard for this procedure has been established so far [16, 68]. For COVID-19 deaths, testing capacities across countries and time differ, making cross-country and temporal comparisons challenging [69]. Moreover, the use of population-level data might introduce bias. Individuals dying prematurely might differ from the population average in their economic characteristics, such as employment rates or productivity. Given well-documented socio-economic health disparities, this could lead to upward bias in our estimates. Yet, in line with common practice in the literature, we opted for average population values for the economic measures used. Additionally, friction periods applied in the FCA were derived from pre-pandemic estimates, which potentially leads to conservative estimation of productivity losses during the pandemic. Finally, our results for low-populated countries are sensitive to changes in the input data and estimates for these should be treated with caution.

## Conclusions

This study of 28 European countries from 2020 to 2023 shows that the burden of productivity losses caused by pandemic mortality was large, highly variable across regions and over time, and sensitive to the baseline mortality and valuation method used. From a health and economic policy perspective, preventing deaths at both working and older ages would yield benefits to productivity and public revenues. At the same time, the unpaid losses experienced should be explicitly accounted for in economic burden of disease studies, as they are substantial. Further, high excess mortality in CEE and the three Baltic states resulted in the greatest economic burden on these societies; this calls for reforms of health and social policies to mitigate threats to economic growth in case of potential future health crises. Finally, better-informed decisions might be made with comprehensive estimates of productivity losses. Using multiple methods as we did provides a broader understanding of the pandemic's economic burden and supports better strategic decision-making.

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**Authors' contributions** PN collected and curated the data, co-designed and handled formal analyses and wrote the first draft of the manuscript. MOO critically assessed the formal analyses and edited the draft of the manuscript. BŁ conceptualised and supervised the formal analyses and edited the draft of the manuscript.

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**Data Availability** This study used publicly available data only. The dataset may be replicated with the sources reported in the manuscript and references.

## Declarations

**Ethics approval and consent to participate** This study used publicly available data only, and no human participants were involved. Approval for the research was granted by the Ethics Committee of the Nicolaus Copernicus University in Toruń, Collegium Medicum in Bydgoszcz (24/10/2023; no. KB 425/2023). Because of the study design and data used, consent to participate does not apply.

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**Competing interests** The authors declare that they have no competing interests.



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## Wstęp

Pandemia COVID-19 stanowiła jedno z największych współczesnych wyzwań zdrowia publicznego, ale także źródło znacznych kosztów ekonomicznych i społecznych. Obciążenie wywołane przez SARS-CoV-2 przejawiało się nie tylko w liczbie zachorowań, hospitalizacji i zgonów, lecz również w utracie potencjału produkcyjnego gospodarek oraz ograniczeniu aktywności ekonomicznej ludności. Dlatego kompleksowa ocena skutków pandemii wymaga ujęcia integrującego perspektywę epidemiologiczną i ekonomiczną. W takim ujęciu osadzona jest niniejsza rozprawa, której przedmiotem jest analiza obciążenia zdrowotnego pandemią COVID-19 oraz jej ekonomicznych konsekwencji, zwłaszcza w zakresie utraty produktywności [1–5].

Badania epidemiologiczne dotyczące COVID-19 dostarczyły danych, pokazujących wpływ pandemii na zdrowie, zarówno pod względem umieralności, jak i zachorowalności [6,7]. Liczne analizy udokumentowały skrócenie oczekiwanego trwania życia [8,9], nadmiarową umieralność [2,10] czy obciążenie zdrowotne spowodowane pandemią pod postacią lat życia skorygowanych o niepełnosprawność [11]. Natomiast dowody naukowe dotyczące społeczno-ekonomicznych konsekwencji pandemii pozostają ograniczone.

Poza standardowymi wskaźnikami epidemiologicznymi, takimi jak śmiertelność czy umieralność, niezwykle przydatnym wskaźnikiem oceny stanu zdrowia populacji jest nadmiarowa umieralność oraz jej pochodne, takie jak np. nadmiarowo utracone lata życia. Wskaźniki ilustrujące nadmiarowe zgony są interesującą alternatywą dla tradycyjnych miar epidemiologicznych, ponieważ statystyki umieralności z powodu COVID-19 okazały się niewiarygodną miarą rzeczywistej liczby ofiar pandemii [12,13]. Wynika to z ograniczonych możliwości identyfikacji zgonów spowodowanych bezpośrednio przez SARS-CoV-2, co zwykle prowadzi do niedoszacowania umieralności z powodu pandemii COVID-19 [2,14].

Nadmiarowa umieralność jest definiowana jako różnica między umieralnością obserwowaną a oczekiwaną (bazową), przy czym ta druga reprezentuje sytuację hipotetyczną, w której pandemia nie wystąpiłaby [15–20]. Pomimo atrakcyjności koncepcyjnej i prostej interpretacji, szacowanie nadmiarowej umieralności napotyka wiele wyzwań. W szczególności wybory metodyczne dotyczące prognozowania umieralności znacząco wpływają na wyniki, prowadząc do różnych szacunków nadmiarowej umieralności w różnych badaniach. Wybory dotyczące zastosowanej miary umieralności, metod statystycznych, okresów referencyjnych (bazowych) oraz zastosowanych różnych częstotliwości danych czasowych (dane dziennie, tygodniowe, miesięczne czy roczne) prowadzą do istotnego zróżnicowania wyników [21,22].

W zakresie obciążenia ekonomicznego, jednym z niedostatecznie zbadanych obszarów pandemii COVID-19 jest oszacowanie strat produktywności (kosztów pośrednich) wynikających z tego kryzysu [23]. Oszacowanie strat produktywności, które reprezentują potencjalną produkcję ekonomiczną niewytworzoną z powodu problemów zdrowotnych, jest kluczowym narzędziem oceny obciążenia ekonomicznego chorobami. Straty te obejmują koszty zarówno umieralności, jak i zachorowalności, i są identyfikowane jako niewykonana produkcja w gospodarce formalnej i nieformalnej (np. prowadzenie gospodarstwa domowego, wolontariat). W związku z tym szacunki strat produktywności dostarczają informacji uzupełniających do badań epidemiologicznych [24–26].

Badania epidemiologiczne szacują wpływ danego czynnika na zdrowie, analizy strat produktywności przekładają natomiast te skutki na warunki ekonomiczne, kwantyfikując straty spowodowane zachorowalnością i przedwczesną umieralnością w wymiarze pieniężnym. Chociaż te dwa podejścia różnią się koncepcyjnie, razem dostarczają bardziej kompleksowej oceny społecznego obciążenia chorobami.

Niniejsza rozprawa łączy trzy komplementarne perspektywy badawcze: syntezę dotychczasowej wiedzy o stratach produktywności związanych z pandemią, analizę nadmiarowej umieralności i utraconych lat życia oraz oszacowanie strat produktywności wynikających z przedwczesnych zgonów. Taki układ pozwala przejść od rozpoznania stanu badań, przez pomiar obciążenia zdrowotnego, do oceny jego konsekwencji ekonomicznych, tworząc spójną i wielowymiarową ocenę skutków pandemii COVID-19.

## Cele pracy

Głównym celem pracy jest ekonomiczna i epidemiologiczna ocena obciążenia umieralnością spowodowaną pandemią COVID-19 w 28 krajach europejskich w latach 2020-2023.

Sformułowano trzy cele szczegółowe:

1. Usystematyzowanie i krytyczna ocena dotychczasowych dowodów naukowych dotyczących strat produktywności związanych z problemami zdrowotnymi wywołanymi pandemią COVID-19 na podstawie populacyjnych badań wtórnych z różnych krajów.
2. Określenie skali obciążenia epidemiologicznego związanego z pandemią COVID-19 w 28 krajach europejskich w latach 2020-2023 na podstawie miar zgonów z powodu COVID-19 oraz nadmiarowych zgonów, w zakresie liczby i częstości zgonów, utraconych lat życia oraz utraconych lat potencjalnie produktywnego życia.
3. Określenie skali obciążenia ekonomicznego związanego z umieralnością przypisywaną pandemii COVID-19 w 28 krajach europejskich w latach 2020-2023 poprzez oszacowanie strat produktywności oraz skutków dla finansów publicznych wynikających zarówno ze zgonów z powodu COVID-19, jak i z nadmiarowych zgonów.

## Materiał i metody

W niniejszej części zaprezentowano podstawy metodyczne oraz charakterystykę materiału badawczego wykorzystanego w trzech publikacjach włączonych do rozprawy. Kolejno omówiono podejście zastosowane w przeglądzie systematycznym, badaniu obciążenia epidemiologicznego oraz analizie ekonomicznych następstw umieralności związanej z pandemią COVID-19.

### Przegląd wcześniejszych wyników badań

Pierwszą opublikowaną pracą z cyklu jest przegląd systematyczny zatytułowany „Productivity Losses due to Health Problems Arising from COVID-19 Pandemic: A Systematic Review of Population-Level Studies Worldwide”. Do przygotowania publikacji zostały użyte wytyczne PRISMA (*Preferred Reporting for Systematic Reviews and Meta-Analyses*) [27]. Protokół przeglądu został prospektywnie zarejestrowany w PROSPERO (numer rejestracyjny CRD42023478059), rejestrze protokołów przeglądów systematycznych z zakresu zdrowia.

Kryteria włączenia do przeglądu: wtórne populacyjne badania ilościowe, wykorzystujące wszystkie metody szacowania strat produktywności wynikających z pandemii COVID-19.

Kryteria wykluczenia z przeglądu: badania ograniczone do określonych subpopulacji (np. pacjentów szpitalnych, ambulatoryjnych i pracowników) lub sektorów gospodarki/branż, badania jakościowe, artykuły redakcyjne, komentarze, poglądy, opinie, listy i rozprawy. Badania wykorzystujące koncepcję wartości statystycznego życia (*value of statistical life*).

Do porównania strat produktywności między włączonymi badaniami zastosowano następujące podejście. Po pierwsze, wyodrębniono dane ilościowe z kwalifikujących się badań i wykluczono te, które nie zawierały wystarczająco szczegółowych danych. Po drugie, aby porównać straty w czasie i różnych walutach oraz wyrazić straty jako udział w produkcie krajowym brutto (PKB), wykorzystano dane Międzynarodowego Funduszu Walutowego dotyczące stóp inflacji, kursów wymiany walut, parytetów siły nabywczej i PKB [28], przyjmując rok 2020 jako bazowy. Po trzecie, aby uwzględnić fakt, że kilka badań przedstawiło szacunki strat dla okresów innych niż pełne lata, przy obliczaniu udziału utraconego PKB zastosowano proporcjonalny stosunek PKB do danego okresu. Po czwarte, aby wyniki były bardziej porównywalne w czasie, zannualizowano straty raportowane w oryginalnych badaniach. Po piąte, aby umożliwić dokładniejsze porównanie między badaniami, dostosowano kategorie wiekowe podane w badaniach źródłowych do trzech przedziałów: 0-39 lat; 40-59 lat i 60+ lat.

**Analiza obciążenia epidemiologicznego**

Drugim badaniem z cyklu jest praca pod tytułem „Beyond death counts: how COVID-19 affected excess mortality and productive life-years lost across 28 European states, 2020-2023” dotycząca obciążenia epidemiologicznego wynikającego z pandemii. W tym badaniu wykorzystano roczne dane Eurostatu [29–31] dotyczące umieralności oraz populacji z 28 państw europejskich (27 krajów Unii Europejskiej (EU) oraz Norwegia) do oszacowania nadmiernego obciążenia zdrowotnego w 5-letnich grupach wiekowych w zależności od płci w latach 2020-2023.

Wykorzystano trzy miary odnoszące się do nadmiernego obciążenia zdrowotnego. Pierwszą jest liczba nadmiarowych zgonów (eD - *excess deaths*), zdefiniowana jako różnica między liczbą obserwowanych zgonów a liczbą zgonów oczekiwanych w przypadku braku pandemii. Wskaźnik ten zapewnia pełniejszy obraz wpływu pandemii wykraczający poza zaraportowane zgony z powodu COVID-19 [32]. Druga miara to nadmiarowo utracone lata życia (eYLL - *excess Years of Life Lost*); ta miara opiera się na wskaźniku utraconych lat życia (*Years of Life Lost*), który jest miarą zdrowia publicznego, który kwantyfikuje wpływ przedwczesnej umieralności poprzez przypisywanie większej wagi zgonom w młodszym wieku. Wskaźnik ilustruje liczbę lat, które osoby przeżyłyby, gdyby nie zmarły przedwcześnie [33,34]. Trzecia miara - nadmiarowo utracone lata potencjalnie produktywnego życia (eYPPLL - *excess Years of Potential Productive Life Lost*) opiera się na wskaźniku utraconych lat potencjalnie produktywnego życia (*Years of Potential Productive Life Lost*), skupiającym się na ekonomicznych i społecznych konsekwencjach przedwczesnej umieralności w populacji w wieku produkcyjnym [35]. Dodatkowo dla eD, eYLL i eYPPLL obliczono wskaźniki standaryzowane wiekiem na 100.000 ludności, stosując standardową populację europejską.

Biorąc pod uwagę szacowanie nadmiarowej umieralności, należy podkreślić, że nie istnieje złoty standard metodyczny, a wybór metody zależy od częstotliwości obserwacji (od dziennych do rocznych), liczby użytych obserwacji czy długości okresu referencyjnego [36]. Do prognozowania umieralności bazowej 2020-2023, zastosowano regresję metodą najmniejszych kwadratów (KMNK), zgodną z wcześniejszymi badaniami nad nadmiarową umieralnością [37–40], ze współczynnikami umieralności (liczba zgonów na 100.000 ludności) regresowanymi względem zmiennej czasowej (rok). Zastosowano 95% przedziały ufności. Oczekiwane zgony w latach 2020-2023 wyznaczono poprzez pomnożenie oczekiwanych współczynników umieralności przez obserwowaną liczebność populacji [32], a nadmiarową umieralność w latach 2020-2023 obliczono jako różnicę między wartościami obserwowanymi a oczekiwanymi. W przypadku oszacowania eYLL, wykorzystano szacunki nadmiarowych zgonów i oczekiwaną długość życia (LE) sprzed pandemii w 2019 roku [41]. Aby oszacować eYPPLL, zamiast LE wykorzystano długość okresu pracy dla każdego kraju w podziale na płeć (46).

Przeprowadzono analizę wrażliwości dla nadmiarowej umieralności w zakresie alternatywnych specyfikacji modelu podstawowego oraz alternatywnego podejścia prognostycznego (zastosowano modele ARIMA (*AutoRegressive Integrated Moving Average*) oraz ETS (*Exponential Smoothing*)). W przypadku eYLL zbadano odporność wyników na alternatywne założenie dotyczące oczekiwanej długości życia. W przypadku eYPPLL zbadano stabilność wyników zastępując wiek wejścia i wyjścia z rynku pracy w zależności od kraju i płci stałą długością życia zawodowego od 20 do 64 roku życia.

**Analiza obciążenia ekonomicznego**

Trzecim badaniem z cyklu jest praca pod tytułem „Paid and unpaid productivity losses across 28 European countries due to excess deaths and COVID-19 deaths from 2020 to 2023" dotycząca obciążenia ekonomicznego wynikającego z pandemii. W tym badaniu wykorzystano retrospektywne, populacyjne dane oraz perspektywę społeczną [44,45] do oszacowania strat produktywności (kosztów pośrednich) związanych z umieralnością przypisywaną pandemii COVID-19 w 28 krajach europejskich (kraje UE oraz Norwegia) w latach 2020-2023.

Do zdefiniowania umieralności związanej z COVID-19 zastosowano dwa alternatywne podejścia: (a) zgony raportowane z kodem ICD-10 U07 jako przyczyna zgonu oraz (b) nadmiarowe zgony oszacowane w ramach analizy epidemiologicznej będącej częścią tej rozprawy. W przypadku obu podejść oszacowano straty produktywności w gospodarce formalnej i nieformalnej [46]. Jako miarę produktywności zastosowano PKB na pracownika skorygowany o parytet siły nabywczej [47]. W przypadku szacunków metodą kapitału ludzkiego (HCA - *human capital approach*) i metodą kosztu alternatywnego (OCA - *opportunity cost approach*) zastosowano 5-procentową stopę dyskontową. Dodatkowo, aby uwzględnić wpływ przyszłego wzrostu gospodarczego w badanych krajach, wykorzystano średnie unijne wskaźniki wzrostu PKB na pracownika w nadchodzących dekadach [43]. W przypadku metody kosztów frykcyjnych (FCA - *friction cost approach*) nie zastosowano dyskontowania ani korekty wzrostu gospodarczego, ponieważ w tej metodzie straty trwają krócej niż rok. Wszystkie straty wyrażono w cenach stałych, przyjmując rok 2020 za rok bazowy oraz stosując zharmonizowany wskaźnik cen konsumpcyjnych jako deflator [48].

W przeciwieństwie do większości badań dotyczących kosztów pośrednich związanych z COVID-19 [25,49,50] w tym badaniu uwzględniono zgony w wieku przedprodukcyjnym (grupy wiekowe 0-4, 5-9, 10-14). Wynika to z faktu, iż osoby umierające w młodym wieku z czasem weszłyby na rynek pracy, a potencjalna strata produktu gospodarczego spowodowana tymi zgonami powinna zostać przeanalizowana (po uwzględnieniu oczekiwanych wskaźników zatrudnienia i zdyskontowanej wartości przyszłej produktywności). Do obliczenia okresu frykcyjnego wykorzystano metodę z badania Hanly i in. [51]. Stosując metodę bazową (1BC), ustalono odpowiednie okresy frykcyjne dla danego roku i kraju. Szacunki strat produktywności oparte na metodzie FCA ograniczono do populacji w wieku 15-74 lat, co oznacza, że populacja przedprodukcyjna została wyłączona. Zgodnie z Ortega-Ortega i in. [46] podzielono nieodpłatną produkcję na kategorie w oparciu o płeć, grupy wiekowe oraz status zatrudnienia. W przypadku osób w kategorii pracujących wyciągnięto średnią z czasu poświęconego na pracę nieodpłatną przez osoby pracujące w pełnym i niepełnym wymiarze godzin. Dla populacji niepracującej uśredniono czas pracy nieodpłatnej wykonywanej przez bezrobotnych, studentów, osoby zajmujące się domem oraz emerytów. Aby określić wartość ekonomiczną utraconej produkcji nierynkowej odwołano się do czasu utraconego w gospodarce formalnej i jego wyceny w PKB. Założono, że praca nieodpłatna jest mniej produktywna niż działalność rynkowa. Wynika to z faktu, że większość aktywności domowych to te, które można zastąpić pracą opłacaną stawkami bliższymi płacy minimalnej, a nie przeciętnej. Dlatego, zgodnie z Łyszczarz [52], minimalną produktywność wyznaczono jako iloraz płacy minimalnej i średniego wynagrodzenia w poszczególnych gospodarkach.

Oprócz analizy strat produktywności zobrazowano również, w jaki sposób straty te wpływają na potencjalne przychody finansów publicznych. Spadek podaży pracy wynikający z przedwczesnej umieralności prowadzi do zmniejszenia całkowitej wytworzonej produkcji. Spadek potencjalnego PKB skutkuje z kolei obniżeniem dochodów ludności i niższym spożyciem, co w konsekwencji uszczupla przychody publiczne poprzez redukcję potencjalnych wpływów z podatków dochodowych i konsumpcyjnych oraz składek na ubezpieczenie społeczne. Taka analiza ilustruje potencjalne straty w przychodach finansów publicznych, które można przypisać spadkowi PKB wywołanemu pandemią. W analizie wykorzystano dane Eurostatu [53] dotyczące udziału w PKB dochodów z czterech najważniejszych podatków (podatku dochodowego od osób fizycznych, podatku dochodowego od osób prawnych, akcyzy oraz podatku od towarów i usług) oraz składek na ubezpieczenia społeczne [1,54].

Przeprowadzono dwie analizy wrażliwości w celu oceny stabilności szacunków: (a) deterministyczną analizę wrażliwości, dotyczącą kluczowych założeń modelowania; (b) analizę niepewności, określającą ilościowo niepewność statystyczną danych wejściowych dotyczących nadmiarowej umieralności.

## Wyniki

### Przegląd wcześniejszych wyników badań

W wyniku przeszukania baz danych (Medline, Embase, Scopus, Web of Science, EconLit, WHO COVID-19 Research Database oraz EuropePMC) zidentyfikowano 15.588 rekordów. Łącznie 9.621 rekordów zostało usuniętych w procesie deduplikacji. Do oceny pełnotekstowej wybrano 52 badania. Ostatecznie 22 z nich spełniły kryteria włączenia. Identyfikacja badań metodami alternatywnymi, takimi jak przeszukiwanie szarej literatury i śledzenie cytowań, pozwoliła na zidentyfikowanie 4.188 rekordów, a po wstępnym etapie selekcji do analizy pełnotekstowej wybrano 87 pozycji. Po tym etapie do przeglądu zakwalifikowano 16 artykułów. Ostatecznie kryteria włączenia spełniło 38 badań. Analiza 96 odrębnych szacunków dla poszczególnych krajów i regionów wykazuje duże zróżnicowanie w poziomie strat produktywności wywołanych pandemią. Najwyższy odnotowany uszczerbek, sięgający 10,36% PKB w przypadku Chin, wynikał niemal w całości (99,9%) z kosztów izolacji (lockdownu), a nie bezpośrednich skutków zdrowotnych spowodowanych wirusem. Wyłączając ten ekstremalny przypadek, typowe straty dla większości badanych państw były znacznie niższe i w 2/3 przypadków nie przekraczały 0,1% PKB. Wyższe wskaźniki, oscylujące wokół 0,5%-2,1% PKB, raportowano głównie w krajach takich jak Hiszpania, Włochy, Wielka Brytania czy USA.

Wyniki przeglądu sugerują, że istnieje wyraźna zależność między poziomem zamożności państwa a wysokością generowanych strat. Kraje o wysokim dochodzie traciły średnio 0,6% PKB, podczas gdy w krajach o niskim dochodzie udział ten był śladowy i wynosił średnio 0,007%. Podobną dysproporcję widać w kosztach przypadających na jeden zgon - od ponad 470 tys. Int$ (dolarów międzynarodowych) w Hiszpanii do wartości poniżej 10 tys. Int$ w wielu krajach Afryki. Co ciekawe, mimo że zgony generują duże straty produktywności, w niektórych analizach to skumulowane koszty absencji chorobowej okazały się wyższe niż całkowite koszty pośrednie przedwczesnej umieralności. Pod względem demograficznym największe obciążenie ekonomiczne generowała grupa wiekowa 40-59 lat. Struktura ta różni się jednak w zależności od zamożności regionu: w krajach bogatych 65% strat z tytułu umieralności przypadało na osoby starsze, podczas gdy w krajach uboższych znaczący udział (25%) miały osoby młode, do 39. roku życia. Analiza według płci wskazuje na wyraźną dominację mężczyzn, którzy odpowiadali za ponad 75% całkowitych strat wynikających ze zgonów, co było tendencją spójną dla wszystkich grup dochodowych.

**Analiza obciążenia epidemiologicznego**

W latach 2020-2023 w 28 państwach europejskich odnotowano łącznie 1.540.034 nadmiarowych zgonów z wyraźnym szczytem w 2021 roku. Analiza wyników wskazuje na istotne zróżnicowanie geograficzne w zakresie zgonów nadmiarowych. Największe obciążenie takimi zgonami poniosła Europa Środkowo-Wschodnia (CEE - *Central and Eastern Europe*), gdzie standaryzowany współczynnik umieralności wyniósł 190 na 100.000 ludności, trzykrotnie przewyższając parametry notowane w zachodniej i północnej części kontynentu. Choć w liczbach bezwzględnych najwięcej zgonów zidentyfikowano w dużych populacjach Włoch, Polski, Niemiec, Francji oraz Hiszpanii, to w ujęciu względnym najwyższą czteroletnią nadmiarową umieralność odnotowano w Bułgarii, Rumunii i Słowacji. Zaobserwowano zróżnicowanie dotyczące płci - większość zmarłych stanowili mężczyźni (54,8%), dla których średni wskaźnik nadmiarowej umieralności (127 zgonów na 100 tys. ludności) był ponad dwukrotnie wyższy niż w przypadku kobiet (61). Zaobserwowano również specyficzną dynamikę czasową. Podczas gdy w większości krajów rok 2021 był okresem krytycznym, w państwach takich jak Niemcy, Austria czy Francja to rok 2022 wiązał się z najwyższymi wskaźnikami zgonów. Ostatni rok badanego okresu przyniósł zmniejszenie umieralności nadmiarowej, szczególnie w Europie Środkowo-Wschodniej, gdzie odnotowano wartości ujemne, przy jednoczesnym utrzymywaniu się relatywnie wysokiej umieralności w krajach wcześniej dotkniętych w stopniu umiarkowanym, takich jak Finlandia czy Holandia.

W analizowanym okresie 2020-2023 skumulowana nadmiarowa umieralność oznaczała stratę blisko 16,7 mln nadmiarowo utraconych lat życia (eYLL), wykazując ścisłą korelację czasową z dynamiką nadmiarowych zgonów (eD) i również osiągając szczyt w 2021 roku. Najwyższe straty w obszarze zgonów przedwczesnych odnotowano w Europie Środkowo-

Wschodniej (34,6% ogółu eYLL), co wynikało z wyższej umieralności osób w wieku przedemerytalnym. Tu również zaobserwowano asymetrię w odniesieniu do płci - mężczyźni generowali 58% całkowitego wskaźnika eYLL, a ich standaryzowany współczynnik (1.304 na 100 tys. ludności) niemal dwukrotnie przewyższał wartości oszacowane dla kobiet. Analiza porównawcza państw wykazała różnice w obciążeniu populacyjnym: od skrajnie wysokich wskaźników w Bułgarii, Litwie i Słowacji, po minimalne straty w Luksemburgu i krajach skandynawskich. Choć rok 2023 przyniósł w większości regionów (w tym w Bułgarii i Rumunii) obniżenie współczynnika eYLL, w Szwecji, odnotowano wzrost wskaźnika, co stanowi istotne odstępstwo od ogólnoeuropejskiej tendencji spadkowej.

Wpływ pandemii na populację w wieku produkcyjnym (20-64 lata) skutkował utratą blisko 2 mln nadmiarowo utraconych lat potencjalnie produktywnego życia (eYPPLL), co stanowiło 12% eYLL. Analiza rozkładu geograficznego wskazuje na szczególną sytuację krajów Europy Środkowo-Wschodniej, które wygenerowały aż 41% strat w tej populacji, przy czym największy udział bezwzględny odnotowano w Polsce (376,6 tys. eYPPLL). Choć szczyt obciążenia przypadł na rok 2021, a w 2023 roku nastąpiło gwałtowne wyhamowanie umieralności, region ten cechował się najwyższymi wskaźnikami względnymi, osiągając na Litwie, Łotwie i w Bułgarii poziomy wyższe niż w Europie Północnej i Zachodniej. Odnotowano większą dysproporcję płciową niż w przypadku dwóch pozostałych wskaźników epidemiologicznych: mężczyźni odpowiadali za ponad 75% całkowitych strat eYPPLL, a ich standaryzowany współczynnik (252 na 100 tys. ludności) ponad dwukrotnie przewyższał wartości oszacowane dla kobiet. Tendencja ta była szczególnie wyraźna w takich krajach jak Finlandia, Szwecja i Austria, gdzie u kobiet odnotowano wartości ujemne, co wskazuje na niższą umieralność w wieku produkcyjnym od prognozowanej.

Analiza trzech miar nadmiarowej umieralności w badanym okresie ujawnia wyraźny gradient wiekowy. Główny ciężar nadmiarowej umieralności spoczął na osobach powyżej 60. roku życia. Podczas gdy w najmłodszych kohortach (0-14 lat) odnotowano spadek umieralności, w grupach starszych dominowała nadmiarowa umieralność, przy czym w kategorii powyżej 85. roku życia wystąpiła wyraźna przewaga zgonów kobiet. Z perspektywy eYLL punkt ciężkości w stosunku do nadmiarowych zgonów przesunął się z grupy najstarszej na kohorty 65-69 oraz 75-79 lat. Szczególną tendencją odnotowaną w latach 2020-2023 jest progresywny wzrost udziału osób młodszych w strukturze strat. W tych latach zaobserwowano progresywny wzrost udziału osób poniżej 60. roku życia w strukturze eYLL. W analizowanym okresie odsetek ten wzrósł ponad dwukrotnie wśród mężczyzn (z 20,0% do 44,7%), natomiast w grupie kobiet zwiększył się z poziomu 9,8% do 14,1%. Tendencja ta znalazła odzwierciedlenie również w eYPPLL, gdzie mimo początkowej dominacji osób w wieku 45+, z biegiem czasu znacznie zwiększył się udział grupy poniżej 45. roku życia - w ostatnim roku analizy odpowiadała ona za 64,4% strat u mężczyzn i aż 80,9% u kobiet.

**Analiza obciążenia ekonomicznego**

Całkowite straty produktywności w gospodarce formalnej wynikające z nadmiarowych zgonów (eD) w latach 2020-2023 we wszystkich 28 krajach łącznie wyniosły 57,6 mld € dla metody kapitału ludzkiego (HCA) oraz 3,1 mld € dla metody kosztów frykcyjnych (FCA). Szacunkowe straty w produktywności w gospodarce nieformalnej okazały się wyższe, osiągając w łączonych szacunkach (straty w grupie pracującej (OCAe) oraz niepracującej (OCAn)) łącznie 72,5 mld €. Straty przypisywane zgonom COVID-19 (CD) były niższe we wszystkich metodach wyceny (np. 35,0 mld € dla HCA), zachowując jednak tę samą hierarchię wyników. W miarach względnych, straty produktywności w gospodarce formalnej w modelu HCA dla eD wyniosły średnio 0,10% PKB (w zakresie od -0,03% do 0,46%), a dla CD 0,06% PKB (od 0,01% do 0,28%). W metodzie FCA średnie straty były znacznie mniejsze i wyniosły odpowiednio 0,005% dla eD oraz 0,004% dla CD. Podobny wzorzec zaobserwowano w gospodarce nieformalnej, przy czym w populacji biernej zawodowo straty zazwyczaj były wyższe niż wśród zatrudnionych.

Niezależnie od metody wyceny, relatywne straty wykazywały wyraźny gradient geograficzny. Wyższe obciążenie względne koncentrowało się w krajach Europy Środkowej i Wschodniej oraz w trzech państwach północnych - Estonii, Litwie i Łotwie. Z kolei kraje Europy Zachodniej i nordyckie odnotowały zazwyczaj mniejsze, a w niektórych przypadkach (jak Malta i Luksemburg) ujemne straty produktywności. Dodatkowo wyniki analizy wskazują na wyraźne zróżnicowanie czasowe strat w poszczególnych krajach i regionach. W przypadku eD kraje CEE oraz Europy Południowej odnotowały kumulację strat w 2021 roku, po której nastąpił wyraźny spadek, prowadzący do wartości ujemnych w 2023 roku w krajach CEE. Odmienną trajektorię zaobserwowano w Europie Zachodniej, gdzie szczyt strat przypadł na rok 2022, oraz w Europie Północnej (szczególnie w Finlandii, Norwegii i Szwecji), gdzie najwyższe obciążenie wystąpiło w 2023 roku. Zgoła inaczej prezentowały się dane dotyczące CD - w tym przypadku obciążenie stratami produktywności było najwyższe w 2021 roku we wszystkich regionach (przy czym dane za rok 2023 były niedostępne dla większości krajów).

Dane w podziale na płeć ujawniają znaczną dysproporcję, wskazując na mężczyzn jako grupę generującą większość strat produktywności we wszystkich podejściach wyceny i miarach umieralności. W ramach metod HCA oraz FCA, nadmiarowe zgony mężczyzn odpowiadały za 82% strat, natomiast w przypadku zgonów COVID-19 wskaźnik ten wyniósł 76%. W obszarze strat w gospodarce nieformalnej różnice między płciami były mniejsze, lecz wciąż znaczące: wśród osób pracujących mężczyźni wygenerowali 74% strat dla eD oraz 66% dla CD. W grupie osób niepracujących rozkład między płciami był bardziej proporcjonalny, jednak udział mężczyzn nadal pozostawał wyższy. Wzorce specyficzne dla wieku różniły się w zależności od przyjętej metody wyceny kosztów pośrednich. Przy HCA oraz OCAe straty produktywności koncentrowały się w populacji w wieku 40-59 lat, która odpowiadała za większość strat zarówno dla eD, jak i CD. Metoda FCA wykazała podobny profil, jednak z większym relatywnym udziałem starszej grupy wiekowej (60-74 lata). W przeciwieństwie do powyższych, przy stratach osób niepracujących (OCAn) straty były najwyższe w grupie wiekowej 60-74 zarówno dla eD, jak i CD.

Straty produktywności w przeliczeniu na mieszkańca wykazywały wyraźne zróżnicowanie między krajami oraz wysoce spójną hierarchię we wszystkich podejściach metodycznych wyceny. Najwyższe straty *per capita*, zarówno dla eD, jak i zgonów CD, koncentrowały się w krajach Europy Środkowo-Wschodniej oraz w trzech krajach bałtyckich, niezależnie od tego, czy analizowano straty w gospodarce formalnej, czy nieformalnej. W krajach nordyckich (Norwegia, Finlandia, Szwecja, Dania) oraz małych gospodarkach, takich jak Luksemburg i Malta, obserwowano znacznie niższe straty w przeliczeniu na mieszkańca.

Obciążenie finansów publicznych wynikające z nadmiarowych zgonów, zsumowane dla wszystkich krajów i lat, wyniosło 19,7 mld € dla HCA oraz 1,1 mld € dla FCA. W ujęciu bezwzględnym największe obciążenie fiskalne odnotowano w Europie Zachodniej. Kolejne miejsca zajęły Europa Środkowo-Wschodnia, Europa Południowa oraz Europa Północna. W przypadku CD, całkowite obciążenie dochodów publicznych było niższe (11,9 mld € dla HCA i 0,7 mld € dla FCA), jednak ranking regionalny pozostał bez zmian.

## Ograniczenia badań

Przeprowadzone badania mają charakter nowatorski i wnoszą wkład do wiedzy na temat epidemiologicznych i ekonomicznych konsekwencji pandemii COVID-19, jednak ich wyniki należy interpretować z uwzględnieniem pewnych ograniczeń. Ograniczenia te wynikają zarówno z przyjętych założeń metodycznych, jak i z charakteru oraz dostępności danych wykorzystanych w poszczególnych analizach.

W przypadku publikacji I należy zachować ostrożność przy porównywaniu danych między poszczególnymi badaniami ze względu na różnorodność specyficznych założeń metodycznych badań włączonych do przeglądu. W przypadku większości badanych prac okres objęty szacunkami ogranicza się do roku 2020, co uniemożliwia wyciągnięcie długo- lub nawet średnioterminowych wniosków dotyczących obciążenia ekonomicznego wynikającego z pandemii. Ponadto, większość badań dotyczyła śmiertelności z powodu COVID-19, rzadko natomiast uwzględniano nadmiarową umieralność.

Głównym ograniczeniem badania II jest wykorzystanie danych rocznych co prowadziło do wyboru klasycznej metody najmniejszych kwadratów do prognozowania umieralności w latach 2020-2023. W konsekwencji przedziały ufności dla szacunków umieralności są dość szerokie. Po drugie, szacunki dla krajów o małej liczbie ludności są obciążone większym ryzykiem błędu, ponieważ niewielka liczba zgonów prowadzi do większej niepewności statystycznej i zwiększonego ryzyka wpływu losowych wahań na uzyskane wyniki. Kolejnym istotnym zastrzeżeniem jest fakt, że odnotowana w 2023 roku nadmiarowa umieralność może wynikać nie tylko z następstw pandemii, ale także z czynników zewnętrznych, takich jak ekstremalne warunki pogodowe czy obciążenie systemów opieki zdrowotnej.

W badaniu III należy uwzględnić następujące zastrzeżenia. Wyniki dotyczą jedynie strat produktywności wynikających ze zgonów przypisywanych pandemii, podczas gdy straty z tytułu zachorowalności na COVID-19 (absencja chorobowa, prezenteizm, opieka nad chorymi) mogą być nawet wyższe niż te wynikające z umieralności. Każda z wykorzystanych metod szacowania kosztów pośrednich posiada własne ograniczenia. W przypadku zgonów bezpośrednio przypisanych COVID-19 wydajność systemów testowania różni się w zależności od kraju i czasu, co utrudnia porównania międzynarodowe i czasowe. Ponadto, wykorzystanie danych na poziomie populacyjnym może wprowadzać błąd systematyczny. Osoby umierające przedwcześnie mogą różnić się od średniej populacyjnej pod względem charakterystyk ekonomicznych, takich jak wskaźniki zatrudnienia czy produktywność. Biorąc pod uwagę dobrze udokumentowane społeczno-ekonomiczne dysproporcje w stanie zdrowia, mogło to prowadzić do przeszacowania wyników. Dodatkowo, do obliczenia okresów frykcyjnych zastosowano model z szacunków przedpandemicznych. W końcu, wyniki dla krajów o małej liczbie ludności są mniej stabilne, w związku z czym szacunki te należy traktować z ostrożnością.

## Podsumowanie

Systematyczny przegląd piśmiennictwa wykazał ograniczenia w literaturze dotyczącej kosztów pośrednich wynikających z COVID-19. We wszystkich włączonych pracach do badania utraty produktywności zastosowano tylko metodę kapitału ludzkiego do analizy strat w gospodarce formalnej. W żadnym badaniu nie zastosowano metody kosztów frykcyjnych, a tylko jedno badanie analizowało straty w gospodarce nieformalnej. Kraje o wysokim dochodzie traciły średnio 0,6% PKB, podczas gdy w krajach o niskim dochodzie udział ten był niewielki i wynosił średnio 0,007%. Podobną dysproporcję zaobserwowano w kosztach przypadających na jeden zgon. Analiza według płci wskazuje na wyraźną dominację mężczyzn, którzy odpowiadali za ponad 3/4 całkowitych strat wynikających ze zgonów, co było tendencją spójną dla wszystkich grup dochodowych.

W latach 2020-2023 w 28 krajach europejskich zidentyfikowano 1,54 mln nadmiarowych zgonów, 16,7 mln nadmiarowo utraconych lat życia oraz blisko 2 mln nadmiarowo utraconych potencjalnie produktywnych lat życia, wykazując przy tym znaczące zróżnicowanie geograficzne, demograficzne i czasowe. Największe obciążenie, zwłaszcza w populacji w wieku produkcyjnym, poniosła Europa Środkowo-Wschodnia oraz kraje bałtyckie, gdzie wskaźniki strat znacznie przewyższały wartości notowane w Europie Północnej i Zachodniej. Analiza ujawniła silne nierówności płciowe na niekorzyść mężczyzn. Choć główny ciężar pandemii spoczął na osobach powyżej 60. roku życia, w końcowej fazie badanego okresu zaobserwowano niepokojącą ewolucję profilu demograficznego strat w kierunku coraz młodszych grup wiekowych. Kolejne lata, szczególnie popandemiczny rok 2023, przyniosły odwrócenie trendu w regionach pierwotnie najsilniej dotkniętych, przy jednoczesnym wystąpieniu opóźnionego efektu w krajach nordyckich.

Szacunkowe koszty pośrednie nadmiarowej umieralności w latach 2020-2023 wyniosły w gospodarce formalnej 57,6 mld € dla HCA, 3,1 mld € dla FCA oraz 72,5 mld € w gospodarce nieformalnej, wykazując przy tym silne zróżnicowanie regionalne, czasowe i demograficzne. Najwyższe straty relatywne względem PKB oraz w przeliczeniu na mieszkańca odnotowano w krajach Europy Środkowo-Wschodniej i państwach bałtyckich, podczas gdy kraje nordyckie i zachodnioeuropejskie charakteryzowały się znacznie niższymi wartościami. Analiza ujawniła głębokie zróżnicowanie między płciami, gdyż mężczyźni odpowiadali za 82% strat w gospodarce rynkowej. Kumulacja obciążeń finansowych dotyczyła głównie osób w wieku 40-59 lat. Dynamika strat w czasie różniła się regionalnie: Europa Środkowo-Wschodnia odnotowała szczyt w 2021 roku, natomiast w krajach północnych i zachodnich najwyższe koszty wystąpiły z opóźnieniem, przypadając na lata 2022-2023. Całość strat przełożyła się na znaczące obciążenie finansów publicznych, przy czym największy ciężar fiskalny w wymiarze bezwzględnym spoczął na budżetach państw Europy Zachodniej.

Konieczne jest prowadzenie dalszych badań nad skutkami pandemii COVID-19, w celu lepszego przygotowania na kolejne potencjalne kryzysy zdrowia publicznego.

W podsumowaniu, należy ponownie podkreślić nowatorstwo niniejszej rozprawy. Polega ono na zintegrowaniu trzech komplementarnych perspektyw badawczych: (1) systematycznej syntezy dowodów dotyczących strat produktywności wywołanych pandemią COVID-19, (2) międzynarodowej oceny nadmiarowej umieralności rozszerzonej o utracone lata życia i lata potencjalnie produktywnego życia oraz (3) porównawczej analizy ekonomicznych skutków zgonów z powodu COVID-19 i nadmiarowych zgonów w Europie. Oryginalny charakter pracy wynika także z zastosowania populacyjnej perspektywy porównawczej obejmującej 28 krajów europejskich i lata 2020-2023, co pozwoliło na uchwycenie nie tylko pandemicznego, ale również postpandemicznego wymiaru obciążeń. Istotnym wkładem rozprawy jest także równoczesne uwzględnienie konsekwencji epidemiologicznych i ekonomicznych, dzięki czemu możliwe było przejście od szacowania liczby zgonów i utraconych lat życia do wyceny strat produktywności w gospodarce formalnej i nieformalnej oraz oszacowania obciążenia finansów publicznych. Na tle dotychczasowej literatury praca wnosi zarówno nową wiedzę empiryczną, jak i uporządkowaną, wielowymiarową ramę oceny skutków pandemii COVID-19.

## Wnioski

1. Duża skala strat ludzkich: Pandemia doprowadziła do 1,54 mln nadmiarowych zgonów, co przełożyło się na utratę niemal 16,7 mln nadmiarowo utraconych lat życia. Rokiem o najwyższych stratach był 2021, odpowiadający za 41% wszystkich utraconych lat.
2. Znaczny koszt ekonomiczny: Łączne straty w produktywności w gospodarce formalnej wyniosły 57,6 mld € dla metody kapitału ludzkiego oraz 3,1 mld € dla metody kosztów frykcyjnych. W gospodarce nieformalnej straty wyniosły 72,5 mld €, co pokazuje, że skutki gospodarcze wykraczają daleko poza ramy samego rynku pracy.
3. Głębokie nierówności regionalne: Kraje Europy Środkowo-Wschodniej i trzy państwa bałtyckie (Estonia, Litwa i Łotwa) poniosły nieproporcjonalnie większe obciążenie epidemiologiczne niż Europa Zachodnia i Północna. W Europie Środkowo-Wschodniej wskaźnik utraconych lat życia był trzykrotnie wyższy niż w krajach nordyckich.
4. Polska w grupie państw z najwyższymi stratami: Polska znalazła się w ścisłej czołówce krajów o najwyższym bezwzględnym obciążeniu epidemiologicznym - zidentyfikowano ponad 213 tys. nadmiarowych zgonów oraz 2,4 mln nadmiarowo utraconych lat życia, co stanowiło ok. 14% strat lat życia całej badanej grupy 28 państw.
5. Znaczna dysproporcja płciowa: Pandemia uderzyła ekonomicznie i epidemiologicznie głównie w mężczyzn, którzy odpowiadali za 82% strat w gospodarce formalnej oraz za 75% nadmiarowo utraconych potencjalnie produktywnych lat życia.
6. Utrata potencjału na rynku pracy: Choć większość zgonów dotyczyła osób starszych, Europa straciła nadmiarowo blisko 2 mln lat potencjalnego produktywnego życia zawodowego. Największe straty w tej kategorii wygenerowały osoby w wieku 40-59 lat.
7. Zjawisko „opóźnionego szczytu”: Podczas gdy w Europie Środkowo-Wschodniej szczyt strat przypadł na rok 2021, kraje takie jak Finlandia, Norwegia i Szwecja odnotowały największe obciążenie nadmiarową umieralnością dopiero w 2023 roku.

8. Wpływ na finanse publiczne: Nadmiarowe zgony spowodowały uszczuplenie dochodów publicznych (podatki, składki) o łączną kwotę 19,7 mld € (dla metody kapitału ludzkiego), co stanowi istotne obciążenie dla budżetów państw.

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Rozprawa doktorska

**Ekonomiczne i epidemiologiczne obciążenie umieralnością spowodowaną pandemią COVID-19**

## Streszczenie

Pandemia COVID-19 oprócz dużego obciążenia zdrowotnego wywołała znaczące konsekwencje gospodarcze na całym świecie, powodując spadek produktu krajowego brutto, wzrost stopy bezrobocia, nierównowagę finansów publicznych i utratę zdolności produkcyjnych. Właściwe podejście do oceny obciążenia umieralnością spowodowaną pandemią obejmuje uwzględnienie zarówno bezpośrednich, jak i pośrednich skutków COVID-19. Biorąc pod uwagę obciążenie ekonomiczne wynikające z pandemii COVID-19, jednym z niedostatecznie zbadanych obszarów jest oszacowanie strat produktywności (kosztów pośrednich). Podczas gdy badania epidemiologiczne szacują wpływ na zdrowie, analizy strat produktywności przekładają te skutki na warunki ekonomiczne, kwantyfikując straty spowodowane zachorowalnością i przedwczesną umieralnością w wymiarze ekonomicznym. Pomimo, że te dwa podejścia różnią się koncepcyjnie, razem zapewniają one bardziej kompleksową ocenę społecznego obciążenia chorobami.

### Cel pracy

Celem pracy jest ekonomiczna i epidemiologiczna ocena obciążenia umieralnością spowodowaną pandemią COVID-19 w 28 krajach europejskich w latach 2020-2023.

### Materiał i metody

Do stworzenia przeglądu systematycznego użyto wytycznych PRISMA. Protokół przeglądu prospektywnie zarejestrowano w rejestrze PROSPERO (numer rejestracyjny CRD42023478059). Przeszukano bazy danych Medline, Embase, Scopus, Web of Science, EconLit, WHO COVID-19 Research i EuropePMC oraz szarą literaturę. Uwzględniono badania na poziomie populacyjnym z wykorzystaniem danych wtórnych. W celu ilościowego

porównania między badaniami oszacowano straty w dolarach międzynarodowych z 2020 roku oraz jako udział w produkcie krajowym brutto.

W ramach analizy epidemiologicznej wykorzystano roczne dane dotyczące umieralności w podziale na płeć i 5-letnie grupy wiekowe za lata 2002-2019 w celu przeprowadzenia predykcji umieralności w 28 krajach europejskich (Unia Europejska i Norwegia) w latach 2020-2023. Zdefiniowano nadmierne obciążenie zdrowotne za pomocą trzech miar: nadmiarowych zgonów (eD), nadmiarowo utraconych lat życia (eYLL) oraz nadmiarowo utraconych lat potencjalnie produktywnego życia (eYPPLL). Nadmiarowe zgony oszacowano poprzez porównanie zgonów obserwowanych i oczekiwanych, a następnie wykorzystano je do obliczeń eYLL i eYPPLL.

W analizie ekonomicznej wykorzystano retrospektywne dane Eurostatu na poziomie populacji oraz perspektywę społeczną do oszacowania strat produktywności (kosztów pośrednich) w gospodarce formalnej i nieformalnej związanych z umieralnością spowodowaną pandemią COVID-19 (nadmiarowe zgony i zgony przypisywane COVID-19) w 28 krajach europejskich (Unia Europejska i Norwegia) w latach 2020-2023. W przypadku strat rynkowych zastosowano metodę kapitału ludzkiego (HCA) i metodę kosztów frykcyjnych (FCA). W przypadku strat nierynkowych zastosowano metodę kosztu alternatywnego (OCA). Przeprowadzono ponadto analizę wpływu umieralności na przychody sektora finansów publicznych.

**Wyniki**

Do przeglądu systematycznego zakwalifikowano 38 badań. W badaniach używano głównie metody kapitału ludzkiego (30 badań), a żadne badanie nie wykorzystywało metody kosztów frykcyjnych. Większość badań (84%) zawierała wyniki dotyczące strat z powodu przedwczesnej umieralności, a jedna czwarta dostarczyła szacunków strat spowodowanych absencją chorobową. W 33 badaniach włączonych do porównania ilościowego zidentyfikowano straty produktywności w zakresie od 0% do 2,1% produktu krajowego brutto; największe straty wystąpiły w krajach o wysokich dochodach i wśród osób w wieku 40-59 lat; straty wśród mężczyzn stanowiły około 3/4 całkowitego obciążenia.

Zidentyfikowano łącznie 1.540.034 nadmiarowych zgonów, co odpowiada 16.695.365 eYLL i 1.997.095 eYPPLL. Europa Środkowo-Wschodnia doświadczyła największej nadwyżki zgonów, podczas gdy kraje północne były najmniej dotknięte tym zjawiskiem. Zaobserwowano zróżnicowanie dotyczące płci, większość zmarłych stanowili mężczyźni (eD - 54,8%, eYLL - 58%, eYPPLL - 75%.). Dodatkowo, analiza ujawnia wyraźny gradient wiekowy. Główny ciężar nadmiarowej umieralności dotyczył osób powyżej 60. roku życia, z największym obciążeniem w grupie wiekowej 85+. Z perspektywy eYLL punkt ciężkości strat przesunął się z grupy najstarszej na kohorty 65-69 oraz 75-79 lat.

Całkowite straty produktywności w gospodarce formalnej z powodu nadmiarowych zgonów w latach 2020-2023 we wszystkich 28 krajach łącznie wyniosły 57,6 mld € w HCA i 3,1 mld € w FCA. Straty produktywności w gospodarce nieformalnej wyniosły 72,5 mld euro, z czego 19,6 mld € przypadało na osoby pracujące, a 52,9 mld € na osoby niepracujące. W przypadku zgonów z powodu COVID-19 straty produktywności były niższe: 35,0 mld € w przypadku HCA, 2,1 mld € w przypadku FCA i 56,2 mld € w przypadku OCA (12,4 mld € w przypadku osób pracujących i 43,8 mld € w przypadku osób niepracujących). Najwyższe względne obciążenie ekonomiczne odnotowano w krajach Europy Środkowo-Wschodniej i trzech państwach bałtyckich (Estonia, Litwa i Łotwa). Straty były wyższe wśród mężczyzn, szczególnie w przypadku strat w gospodarce rynkowej (>80% całości). Dodatkowo zidentyfikowano heterogeniczne wzorce czasowe w różnych regionach: kraje Europy Środkowo-Wschodniej i Południowej odnotowały największe straty w 2021 r., kraje zachodnie w 2022 r., a północne w 2023 r.

**Wnioski**

1. Duża skala strat ludzkich: Pandemia doprowadziła do 1,54 mln nadmiarowych zgonów, co przełożyło się na utratę niemal 16,7 mln nadmiarowo utraconych lat życia. Rokiem o najwyższych stratach był 2021, odpowiadający za 41% wszystkich utraconych lat.
2. Znaczny koszt ekonomiczny: Łączne straty w produktywności w gospodarce formalnej wyniosły 57,6 mld € dla metody kapitału ludzkiego oraz 3,1 mld € dla metody kosztów frykcyjnych. W gospodarce nieformalnej straty wyniosły 72,5 mld €, co pokazuje, że skutki gospodarcze wykraczają daleko poza ramy samego rynku pracy.

3. Głębokie nierówności regionalne: Kraje Europy Środkowo-Wschodniej i trzy państwa bałtyckie (Estonia, Litwa i Łotwa) poniosły nieproporcjonalnie większe obciążenie epidemiologiczne niż Europa Zachodnia i Północna. W Europie Środkowo-Wschodniej wskaźnik utraconych lat życia był trzykrotnie wyższy niż w krajach nordyckich.
4. Polska w grupie państw z najwyższymi stratami: Polska znalazła się w ścisłej czołówce krajów o najwyższym bezwzględnym obciążeniu epidemiologicznym - zidentyfikowano ponad 213 tys. nadmiarowych zgonów oraz 2,4 mln nadmiarowo utraconych lat życia, co stanowiło ok. 14% strat lat życia całej badanej grupy 28 państw.
5. Znaczna dysproporcja płciowa: Pandemia uderzyła ekonomicznie i epidemiologicznie głównie w mężczyzn, którzy odpowiadali za 82% strat w gospodarce formalnej oraz za 75% nadmiarowo utraconych potencjalnie produktywnych lat życia.
6. Utrata potencjału na rynku pracy: Choć większość zgonów dotyczyła osób starszych, Europa straciła nadmiarowo blisko 2 mln lat potencjalnego produktywnego życia zawodowego. Największe straty w tej kategorii wygenerowały osoby w wieku 40-59 lat.
7. Zjawisko „opóźnionego szczytu”: Podczas gdy w Europie Środkowo-Wschodniej szczyt strat przypadł na rok 2021, kraje takie jak Finlandia, Norwegia i Szwecja odnotowały największe obciążenie nadmiarową umieralnością dopiero w 2023 roku.
8. Wpływ na finanse publiczne: Nadmiarowe zgony spowodowały uszczuplenie dochodów publicznych (podatki, składki) o łączną kwotę 19,7 mld € (dla metody kapitału ludzkiego), co stanowi istotne obciążenie dla budżetów państw.

Doctoral dissertation

**Economic and epidemiological burden of mortality associated with the COVID-19 pandemic**


## Summary

In addition to its substantial public health burden, the COVID-19 pandemic generated significant economic consequences worldwide, including a decline in gross domestic product, rising unemployment, public finance imbalances, and loss of productive capacity. An appropriate approach to assessing the excess mortality burden caused by the pandemic should account for both the direct and indirect effects of COVID-19. As for the economic burden of the COVID-19 pandemic, one under-researched area is the estimation of productivity losses (indirect costs). While epidemiological studies assess the impact on health, productivity loss analyses translate these effects into economic terms by quantifying losses resulting from morbidity and premature mortality. Although these two approaches differ conceptually, together they provide a more comprehensive assessment of the societal burden of disease.

### Aim of the study

The dissertation aims to provide an economic and epidemiological assessment of the mortality burden caused by the COVID-19 pandemic in 28 European countries in the years 2020-2023.

### Materials and methods

The systematic review was conducted in accordance with the PRISMA guidelines. The review protocol was prospectively registered in the PROSPERO registry (registration number CRD42023478059). Medline, Embase, Scopus, Web of Science, EconLit, WHO COVID-19 Research, and EuropePMC databases were searched, along with grey literature sources. Population-level studies using secondary data were included. For quantitative cross-study comparison, losses were estimated in 2020 international dollars and as a share of gross domestic product.

In the epidemiological analysis, annual mortality data stratified by sex and 5-year age groups for the years 2002-2019 were used to predict mortality in 28 European countries (the European Union and Norway) for the years 2020-2023. Excess health burden was defined using three measures: excess deaths (eD), excess Years of Life Lost (eYLL), and excess Years of Potential Productive Life Lost (eYPPLL). Excess deaths were estimated by comparing observed and expected deaths and were subsequently used to calculate eYLL and eYPPLL.

In the economic analysis, retrospective Eurostat population-level data and a societal perspective were used to estimate productivity losses (indirect costs) in the formal and informal economy associated with mortality caused by the COVID-19 pandemic (excess deaths and COVID-19-attributable deaths) in 28 European countries (the European Union and Norway) during 2020-2023. For market losses, the Human Capital Approach (HCA) and the Friction Cost Approach (FCA) were applied. For non-market losses, the Opportunity Cost Approach (OCA) was used. In addition, the impact of mortality on public finance revenues was analysed.

**Results**

A total of 38 studies were included in the systematic review. The Human Capital Approach was the dominant method used in the studies (30 studies), while none applied the Friction Cost Approach. Most studies (84%) reported results on losses due to premature mortality, and one quarter provided estimates of losses caused by sickness-related absenteeism. In the 33 studies included in the quantitative comparison, productivity losses ranged from 0% to 2.1% of gross domestic product; the greatest losses were observed in high-income countries and among individuals aged 40-59 years; losses among men accounted for approximately three-quarters of the total burden.

A total of 1,540,034 excess deaths were identified, corresponding to 16,695,365 eYLL and 1,997,095 eYPPLL. Central and Eastern Europe experienced the highest excess mortality burden, whereas the Northern countries were least affected. Sex differences were also observed, with men accounting for the majority of the burden (eD: 54.8%, eYLL: 58%, eYPPLL: 75%). In addition, the analysis revealed a pronounced age gradient. The main burden of excess mortality concerned individuals aged over 60 years, with the highest burden observed in the

85+ age group. From the perspective of eYLL, the burden shifted from the oldest age group to the 65-69 and 75-79 age cohorts.

Total productivity losses in the formal economy due to excess deaths in 2020-2023 across all 28 countries amounted to €57.6 billion under the HCA and €3.1 billion under the FCA. Productivity losses in the informal economy amounted to €72.5 billion, of which €19.6 billion was attributable to employed individuals and €52.9 billion to non-employed individuals. For COVID-19 deaths, productivity losses were lower: €35.0 billion under the HCA, €2.1 billion under the FCA, and €56.2 billion under the OCA (€12.4 billion among the employed and €43.8 billion among the non-employed). The highest relative economic burden was observed in Central and Eastern European countries and in the three Baltic states (Estonia, Lithuania, and Latvia). Losses were higher among men, particularly in the market economy (>80% of the total). Moreover, heterogeneous temporal patterns were identified across regions: Central and Southern European countries experienced the greatest losses in 2021, Western countries in 2022, and Northern countries in 2023.

**Conclusions**

1. Large scale of human losses: The pandemic resulted in 1.54 million excess deaths, translating into a loss of nearly 16.7 million excess Years of Life Lost. The year 2021 was associated with the highest burden, accounting for 41% of all excess Years of Life Lost.
2. Substantial economic costs: Total productivity losses in the formal economy amounted to €57.6 billion under the Human Capital Approach and €3.1 billion under the Friction Cost Approach. In the informal economy, losses reached €72.5 billion, demonstrating that the economic consequences extended far beyond the labour market.
3. Profound regional inequalities: Central and Eastern European countries and the three Baltic states (Estonia, Lithuania, and Latvia) bore a disproportionately higher epidemiological burden than Western and Northern Europe. In Central and Eastern Europe, the excess Years of Life Lost rate was three times higher than in the Nordic countries.
4. Poland among the countries with the highest losses: Poland was among the countries with the highest absolute epidemiological burden, with more than 213,000 excess

deaths and 2.4 million excess Years of Life Lost identified, accounting for approximately 14% of the total years lost across the 28 countries analysed.

5. Marked sex disparities: The pandemic affected men disproportionately, both economically and epidemiologically, as they accounted for 82% of formal economy losses and 75% of excess Years of Potential Productive Life Lost.
6. Loss of labour market potential: Although most deaths occurred among older individuals, Europe experienced nearly 2 million excess Years of Potential Productive Life Lost. The greatest burden in this category was observed in individuals aged 40-59 years.
7. The phenomenon of a "delayed peak": While the burden peaked in Central and Eastern Europe in 2021, countries such as Finland, Norway, and Sweden experienced the highest excess mortality burden only in 2023.
8. Fiscal impact on public finances: Excess deaths caused a reduction in public revenues (taxes and social contributions) amounting to €19.7 billion in total (under the Human Capital Approach), representing a significant burden for national budgets.

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## Załączniki

**Wykaz stosowanych skrótów.**

**ARIMA** - AutoRegressive Integrated Moving Average

**CEE** - Europa Środkowo-Wschodnia (Central and Eastern Europe)

**CD** - zgony z powodu COVID-19

**COVID-19** - Coronavirus disease 2019

**eD** - Nadmiarowe zgony (Excess deaths)

**EU**- Unia Europejska (European Union)

**ETS** - Exponential Smoothing

**eYLL** - Nadmiarowo utracone lata życia (excess Years of Life Lost)

**eYPPLL** - Nadmiarowo utracone lata potencjalnie produktywnego życia (excess Years of Potential Productive Life Lost)

**FCA** - Metoda kosztów frykcyjnych (Friction Cost Approach)

**HCA** - Metoda kapitału ludzkiego (Human Cost Approach)

**ICD-10** - International Statistical Classification of Diseases and Related Health Problems 10th Revision

**KMNK** - Regresja metodą najmniejszych kwadratów (Ordinary least squares)

**LE** - Oczekiwana długość życia (Life expectancy)

**OCA** - Metoda kosztu alternatywnego (Opportunity Cost Approach)

**OCAe** - Metoda kosztu alternatywnego dla pracujących (Opportunity Cost Approach for employed)

**OCAn** - Metoda kosztu alternatywnego dla niepracujących (Opportunity Cost Approach for non-employed)

**PKB** - Produkt krajowy brutto

**PRISMA** - Preferred Reporting for Systematic Reviews and Meta-Analyses

**SARS-CoV-2** - Severe acute respiratory syndrome coronavirus 2

**USA** - Stany Zjednoczone Ameryki (United Stated of America)

**Uniwersytet Mikołaja Kopernika w Toruniu**
**Collegium Medicum im L. Rydygiera w Bydgoszczy**
**KOMISJA BIOETYCZNA**
**Ul. M. Skłodowskiej-Curie 9, 85-094 Bydgoszcz, tel.(052) 585-35-63**

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**KB 425/2023** Bydgoszcz, 24.10.2023 r.

Działając na podstawie art.29 ustawy z dnia 5.12.1996 r. o zawodzie lekarza (Dz.U. z 1997 r. Nr 28 poz. 152, wraz z późniejszymi zmianami), rozporządzenia Ministra Zdrowia z dnia 26.01.2023r. w sprawie komisji bioetycznej oraz Odwoławczej Komisji Bioetycznej (Dz. U. 2023 poz. 218) oraz Zarządzenia nr 108 Rektora Uniwersytetu Mikołaja Kopernika w Toruniu z dnia 31 maja 2023r. w sprawie powołania komisji bioetycznej oraz zgodnie z zasadami zawartymi w DH i GCP.

**Komisja Bioetyczna przy UMK w Toruniu, Collegium Medicum w Bydgoszczy**

na posiedzeniu w dniu **24.10.2023 r.** przeanalizowała wniosek, który złożył kierownik badania:

**dr hab. Błażej Łyszczarz, prof. UMK**
**Katedra Ekonomiki Zdrowia**
**Collegium Medicum w Bydgoszczy UMK w Toruniu**

z zespołem w składzie:

**dr hab. Błażej Łyszczarz, prof. UMK, dr Marta Ortega-Ortega, lek. Paweł Niewiadomski**

w sprawie badania:

**„Ekonomiczne i epidemiologiczne obciążenie umieralnością i zachorowalnością spowodowanymi pandemią COVID-19".**

Po zapoznaniu się ze złożonym wnioskiem i w wyniku przeprowadzonej dyskusji oraz głosowania Komisja podjęła

**Uchwałę o pozytywnym zaopiniowaniu wniosku**

w sprawie przeprowadzenia badań w zakresie określonym we wniosku

***Zgoda obowiązuje od daty podjęcia uchwały (24.10.2023 r.) do końca 2027 r.***

*Wydana opinia dotyczy tylko rozpatrywanego wniosku z uwzględnieniem przedstawionego projektu; każda zmiana i modyfikacja wymaga uzyskania odrębnej opinii.*

Prof. dr hab. med. Mariusz Dubiel

Przewodniczący Komisji Bioetycznej

Otrzymuje:
dr hab. Błażej Łyszczarz, prof. UMK
Katedra Ekonomiki Zdrowia
Collegium Medicum w Bydgoszczy UMK w Toruniu

**Dr hab. Błażej Łyszczarz, prof. UMK**

**Oświadczenie współautora o udziale w publikacji**

**I**

Niewiadomski P, Ortega-Ortega M, **Łyszczarz B**. Productivity Losses due to Health Problems Arising from COVID-19 Pandemic: A Systematic Review of Population-Level Studies Worldwide. Appl Health Econ Health Policy. 2025;23(2):231-251. doi:10.1007/s40258-024-00935-8

Udział autorski: koncepcja i metodyka badania, interpretacja wyników, konsultacje i opieka, nadzór nad badaniem, korekta pracy przed złożeniem do druku.

**II**

Niewiadomski P, Wojtasik J, **Łyszczarz B**. Beyond death counts: how COVID-19 affected excess mortality and productive life-years lost across 28 European states, 2020-2023. Front Public Health. 2026;13:1720864. doi:10.3389/fpubh.2025.1720864

Udział autorski: koncepcja i metodyka badania, interpretacja wyników, konsultacje i opieka, nadzór nad badaniem, korekta pracy przed złożeniem do druku

**III**

Niewiadomski P, Ortega-Ortega M, **Łyszczarz B**. Paid and unpaid productivity losses across 28 European countries due to excess deaths and COVID-19 deaths from 2020 to 2023. Eur J Health Econ. doi: 10.1007/s10198-026-01916-5

Udział autorski: koncepcja i metodyka badania, interpretacja wyników, konsultacje i opieka, nadzór nad badaniem, korekta pracy przed złożeniem do druku

Signature Not Verified
Dokument podpisany przez Błażej Łyszczarz; UMK
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Data i podpis współautora

**Ph. D. Marta Ortega-Ortega, Associate Professor**

**Oświadczenie współautora o udziale w publikacji**

**I**

Niewiadomski P, **Ortega-Ortega M**, Łyszczarz B. Productivity Losses due to Health Problems Arising from COVID-19 Pandemic: A Systematic Review of Population-Level Studies Worldwide. Appl Health Econ Health Policy. 2025;23(2):231-251. doi:10.1007/s40258-024-00935-8

Udział autorski: koncepcja badania, interpretacja wyników, zbieranie danych, korekta pracy przed złożeniem do druku

Author contributions: research concept, interpretation of results, data collection, and proofreading the manuscript prior to submission.

**II**

Niewiadomski P, **Ortega-Ortega M**, Łyszczarz B. Paid and unpaid productivity losses across 28 European countries due to excess deaths and COVID-19 deaths from 2020 to 2023. Eur J Health Econ. doi: 10.1007/s10198-026-01916-5

Udział autorski: krytyczna ocena metodyki badania, korekta pracy przed złożeniem do druku.

Author contributions: critical assessment of the research methodology, and proofreading the manuscript prior to submission.

Firmado por ORTEGA ORTEGA MARTA - ***6340** el día 21/04/2026 con un certificado emitido por AC FNMT Usuarios

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Data i podpis współautora

**Mgr inż. Jakub Wojtasik**

**Oświadczenie współautora o udziale w publikacji**

**I**

Niewiadomski P, **Wojtasik J**, Łyszczarz B. Beyond death counts: how COVID-19 affected excess mortality and productive life-years lost across 28 European states, 2020-2023. Front Public Health. 2026;13:1720864. doi:10.3389/fpubh.2025.1720864

Udział autorski: przeprowadzenie analizy statystycznej, pisanie manuskryptu.

20.04.2026 Jakub Wojtasik

Data i podpis współautora