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Abstract

Background: Socioeconomic inequalities remain major determinants of population health, and small-area measures of deprivation constitute essential tools for monitoring and addressing these inequalities. In this study, we developed the updated 2021 Portuguese version of the European Deprivation Index (EDI-PT 2021), described its spatial distribution, and evaluated its association with all-cause mortality.

Results: Using data from the 2021 European Union Statistics on Income and Living Conditions (EU-SILC) survey, we constructed an indicator of individual deprivation based on fundamental needs associated with both objective and subjective poverty. Variables common to both EU-SILC and the 2021 Portuguese census were identified and tested for association with individual deprivation to derive weights. The EDI-PT 2021 was calculated for 10,401 census block groups and subsequently aggregated to parish and municipality levels. The final index comprised nine weighted variables reflecting marital status, country of birth, education, employment, occupation, housing characteristics, household composition, and tenure status. Spatial distribution revealed marked territorial inequalities, with higher deprivation concentrated in southern and inland regions and lower deprivation along the northern and central coastal corridor. Associations with all-cause mortality, estimated using Bayesian spatial models, showed a clear dose–response relationship, with progressively higher mortality risks across deprivation quintiles. Compared with the least deprived areas, the most deprived exhibited a relative risk of 1.090 (95% Credible Interval: 1.067-1.115) at parish level and 1.103 (1.062-1.145) at municipality level.

Conclusions: The EDI-PT 2021 captures contemporary socioeconomic deprivation and shows significant associations with mortality across spatial scales, providing a robust tool for epidemiological research, surveillance, and evidence-based territorial planning.

Key-words: social determinants of health; Inequalities; neighbourhoods; Health Geography; exclusion.

1. Introduction

Socioeconomic inequalities remain among the most powerful determinants of population health (1). Differences in access to material resources, education, employment, and housing conditions influence patterns of morbidity and mortality across societies, contributing to persistent health disparities both within and between countries (2). Addressing socioeconomic inequalities has therefore become a central priority in public health research and policy (2) specially because social gradients in health continue to be documented despite overall improvements in population health indicators (3).

Small-area measures of socioeconomic deprivation play a fundamental role in the identification, monitoring, and reduction of health inequalities (4). Area-level deprivation measures enable researchers and policymakers to quantify multidimensional disadvantage at fine spatial scales, capturing variations in living conditions that may not be evident at larger geographical levels. By integrating information across multiple socioeconomic domains, deprivation indices provide a synthetic indicator of the cumulative impact of disadvantage within communities (5). These measures are widely used in research to investigate geographical health inequalities and environmental injustice, guide resource allocation, and support evidence-based planning (6). In addition, area-level indicators are often based on publicly available data that can approximate

otherwise difficult-to-obtain individual-level information, and are particularly well suited for population-based studies and policy development (4).

The European Deprivation Index (EDI) represents a major methodological advance in the measurement of socioeconomic deprivation across European countries. Developed within a multinational collaborative and interdisciplinary framework (7), the EDI was designed to ensure cross-national comparability while maintaining sensitivity to national contexts. Its construction relies on a rigorous methodological approach that integrates individual-level data from the European Union Statistics on Income and Living Conditions (EU-SILC) survey with aggregated census data. This dual-data framework enables the identification of socioeconomic characteristics associated with individual deprivation and allows the translation of these characteristics into small-area indicators applicable across the entire population. The methodological framework underlying the EDI involves three sequential stages (7): (1) the development of an individual deprivation indicator based on fundamental needs; (2) the identification of variables available at both individual and ecological levels; and (3) the construction of an ecological deprivation index through weighted aggregation of selected variables.

The Portuguese version of the European Deprivation Index (EDI-PT) was first developed using data from the 2006 EU-SILC and national census 2001 (8) and subsequently updated using data from the 2011 census and EU-SILC survey (6). These earlier versions demonstrated strong associations with key health outcomes, including mortality (9), old-age survival (10, 11), life expectancy (12), disease-predictive biomarkers (13), infectious diseases such as tuberculosis, (14, 15), sexually transmitted infections (16) or COVID-19 (17), childhood obesity (18, 19), hospital death (20), among other health outcomes. The ability of the EDI to detect gradients and differences in mortality and other health

indicators confirmed its value as a sensitive and reliable tool for the assessment of socioeconomic inequalities.

However, socioeconomic conditions are dynamic and evolve in response to demographic, economic, and social transformations and the concept of deprivation is inherently time- and context-dependent and requires periodic reassessment (21, 22). The past decade has been marked by substantial societal changes, including economic recovery following the global financial crisis (23), migration flows, technological expansion, and shifts in household composition (24). More recently, the COVID-19 pandemic introduced new forms of social vulnerability and amplified pre-existing inequalities (25). Moreover, following the global financial crisis, particularly in urban centres, transnational gentrification and the ongoing housing crisis have reshaped neighbourhood socioeconomic composition, contributing to spatial inequalities and affecting population health (23, 26, 27). Collectively, these transformations underscore the need to periodically update deprivation measures to ensure their continued relevance, sensitivity to emerging vulnerabilities, and accuracy in capturing contemporary patterns of socioeconomic disadvantage.

Therefore, the objectives of this study were to: (1) develop the updated 2021 version of Portuguese European Deprivation Index (EDI-PT 2021); (2) describe its spatial distribution across Portugal at multiple progressively detailed geographical levels; and (3) evaluate its association with all-cause mortality using spatial statistical modelling.

2. Materials and Methods

2.1. Data sources

Individual-level data used to construct the deprivation indicator were obtained from the European Union Statistics on Income and Living Conditions (EU-SILC) 2021 survey (28). EU-SILC is a standardized cross-sectional and longitudinal survey conducted annually across European Union member states to provide harmonized information on income, poverty, social exclusion, and living conditions. The survey follows a common methodological framework that ensures comparability across countries. The questionnaire includes a module devoted to material deprivation, capturing enforced lacks defined as goods or services that households cannot afford due to financial constraints rather than voluntary choices and preferences (29). In Portugal, EU-SILC has been conducted annually since 2006 by Statistics Portugal (Instituto Nacional de Estatística, INE). For the present study, we used data from the 2021 EU-SILC cross-sectional survey, conducted under a harmonized methodological framework across all European Union member states. In Portugal, data collection was performed throughout 2021 following standardized procedures defined by Eurostat. The EU-SILC 2021 sample included 23,731 individuals aged 16 years or older and 10,973 households.

Ecological-level data were obtained from the 2021 Portuguese Population and Housing Census conducted by Statistics Portugal (30). The Portuguese census is universal and exhaustive, covering the entire resident population and providing detailed demographic, socioeconomic, and housing information at fine spatial resolution. The European Deprivation Index for Portugal (EDI-PT 2021) was calculated at the census block group level, maintaining compatibility with earlier Portuguese versions. The census block

groups (N=10,401) include, on average, 994.4 individuals (SD=409.0) and 575.1 households (SD=136.5). The use of small-area units allows detection of localized socioeconomic inequalities that may not be visible at aggregated spatial levels. In addition to census block groups, the index was aggregated to parish (average individuals =1,934.5; SD=3,345.1; households=3,839.0; SD=7,187.5) and municipality levels (average individuals=19,420.4; SD=33,581.4; households=29,375.0; SD=56,440.0) to enable comparisons across multiple spatial scales and to assess potential scale-related effects. All census variables included in the index were expressed as proportions relative to the total number of individuals or households within each spatial unit.

Data on all-cause mortality for the period 2019–2023 were obtained from Statistics Portugal. Mortality records included counts of deaths and population denominators stratified by age group, sex, and geographical unit (municipality and parish). To reduce statistical instability due to small population sizes, mortality counts were aggregated across consecutive years centred on the 2021 census year, a common strategy in spatial epidemiology to address small-number problems. Population denominators corresponding to the same period were obtained from official population estimates.

2.2. Construction of the European Deprivation Index (EDI-PT 2021)

The construction of the updated Portuguese European Deprivation Index followed the standardized three-step methodology developed within the European Deprivation Index framework (7). This methodology integrates individual-level and ecological-level data to derive a deprivation index applicable to small geographical areas and comparable across time. The three-step procedure includes the construction of an individual deprivation indicator, the identification of shared variables between individual and ecological datasets, and the construction of the final ecological deprivation index.

2.2.1. Step 1: Construction of the individual deprivation indicator

Selection of candidate fundamental needs

The first stage consisted of identifying candidate fundamental needs using deprivation-related items available in the EU-SILC 2021 survey. Fundamental needs were defined as goods or services considered necessary within the national sociocultural context and possessed by the majority of households. Items were classified as candidate fundamental needs when fewer than 50% of households reported being unable to afford them.

Earlier versions relied on a limited number of material deprivation items. Moreover, some of material deprivation items have been no more available in the survey (Having a colour TV, having a washing machine, having a phone (including mobile phone)). These needs were registered at household level. At individual level, the survey includes new items whereas the 2021 update incorporates thirteen fundamental needs reflecting contemporary living standards and social participation. These needs included the ability to cover unexpected financial expenses, taking a one-week annual holiday away from home, consuming a meal containing meat, fish or vegetarian equivalent every two days, keeping the home adequately warm, having access to a car, having access to a computer, replacing worn-out furniture, replacing worn-out clothes, having two pairs of properly fitting shoes, participating in social gatherings with friends or family, participating in leisure activities, spending a small amount of money weekly on oneself, and having internet access at home for personal use. This expansion enhances the sensitivity of the deprivation indicator to emerging forms of disadvantage while maintaining conceptual continuity with previous EDI versions. As in earlier iterations, fundamental needs were identified based on their prevalence in the population and their association with objective

and subjective poverty measures, with deprivation defined as the minimum number of needs lacking by financial constraints.

Identification of fundamental needs associated with poverty

Each candidate need was evaluated to determine its association with both objective and subjective poverty. Objective poverty was defined using household income thresholds consistent with national poverty definitions, i.e., if his/ her household income is below 60% of the national median equivalised disposable income, i.e., the total income of a household, after tax and other deductions, that is available for spending or saving, divided by the number of household members converted into equalised adults. In Portugal, in 2021, that poverty threshold was 6,655 euros. Subjective poverty was evaluated by the EU-SILC Likert-scale question ‘ability to make ends meet’ (from 1-with great difficulty to 6-very easily). To determine the threshold at which a person felt poor, we carried out univariable logistic regressions between objective poverty (‘poor’/‘not poor’, based on the 6,655 euros threshold) and subjective poverty, dichotomized according to all combinations of answers to the question ‘ability to make ends meet’. Wald chi-square statistic (χ^2) was used to determine the dichotomization with the best fit; the higher χ^2 the better. The answer 1 and 2 (with great difficulty, with difficulty) versus the others (with some difficulty, fairly easily, easily and very easily) had the highest χ^2 . Based on that threshold, 21.2% of the Portuguese individuals were subjectively poor. Univariable logistic regression models were fitted to assess the association between each candidate fundamental need and poverty indicators. Candidate needs significantly associated with both objective and subjective poverty were retained as fundamental needs.

Definition of the individual deprivation indicator

A binary individual deprivation indicator was constructed based on the minimal number of fundamental needs. It was defined by at least one fundamental needs lacking, at least two, at least three and so on. Logistic regression models were used to determine the threshold number of unmet needs that best predicted both objective and subjective poverty. The threshold selected was those that have a highest Wald chi-square statistic. This binary deprivation indicator served as the dependent variable in subsequent modelling steps linking individual characteristics to deprivation status.

2.2.2. Step 2: Identification and dichotomization of shared variables

Selection of shared variables

The second stage involved identifying variables available in both the EU-SILC dataset and the Portuguese 2021 census. These shared variables allowed translation of individual-level deprivation associations into ecological-level indicators applicable across all geographical areas. Variables were selected based on conceptual relevance to socioeconomic deprivation and on the availability of comparable definitions across the two datasets. All variables were recoded to ensure consistency between EU-SILC and census classifications.

Dichotomization of variables

Variables with multiple response categories were dichotomized to allow the calculation of proportions at the ecological level. For each candidate variable, alternative dichotomization thresholds were evaluated using logistic regression models linking the variable to individual deprivation status. We selected the dichotomization which yield the

best model fit (highest Wald χ^2). Once dichotomized, proportions corresponding to each variable category were calculated for each census block group, parish and municipality. These proportions constituted the ecological-level measures used in the final deprivation model.

2.2.3. Step 3: Construction of the ecological deprivation index

Selection of variables for the final model

A multivariable logistic regression model was fitted using the individual deprivation indicator as the dependent variable and the candidate shared variables as independent variables. Variables that remained statistically significant after mutual adjustment were retained in the final ecological deprivation model. Regression coefficients obtained from this multivariable model were interpreted as weights, reflecting the relative importance of each variable in explaining deprivation. These coefficients quantified the strength of association between individual deprivation and each socioeconomic characteristic.

Standardization of variables

Prior to index calculation, each retained variable was standardized using z-score normalization. Standardization involved subtracting the national mean and dividing by the national standard deviation for each variable.

Calculation of the EDI score

The ecological deprivation score was calculated as the weighted sum of standardized variables using regression coefficients obtained from the multivariable model. Each standardized variable contributed to the index according to its corresponding coefficient,

representing its relative importance in explaining deprivation. The resulting continuous deprivation score represented the relative level of deprivation in each spatial unit compared to the national average. Higher scores indicated greater levels of deprivation. To facilitate interpretation and enable comparison across geographical areas, the continuous EDI scores were categorized into quintiles. Quintile thresholds were defined using the national distribution of index scores. Quintile 1 represented the least deprived areas, while quintile 5 represented the most deprived areas.

2.3. Spatial distribution of deprivation

EDI scores were calculated for census block groups, parish and municipality levels. The use of multiple spatial scales allowed assessment of geographical variation in deprivation patterns and evaluation of potential scale-related effects. Spatial distribution maps were generated to visualize geographical patterns of deprivation across Portugal. Mapping procedures were conducted using geographic information systems (GIS), more precisely ArcGIS Pro 3.6.0.

2.4. Association with all-cause mortality

To estimate associations with all-cause mortality, we used a hierarchical Bayesian spatial model. Bayesian inference combines prior distributions on model parameters with the data likelihood to derive posterior distributions. A key advantage of the Bayesian approach is its ability to account for uncertainty in the estimates, as well as its flexibility and capacity to address issues such as spatial autocorrelation and the high variability often observed in small areas (31). In addition, to ensure that associations were not driven by differences in the age structure of Portuguese parishes, mortality rates were age-standardized using the indirect method (32). Portuguese mortality rates by sex and age

group (5-year age groups) were used as the reference to compute the expected number of deaths.

We assumed that the response variable, deaths (O_i), in each i th area followed a Poisson distribution, where E_i represents the expected number of deaths and θ_i the relative risk (RR) (Eq. 1):

$$O_i \sim \text{Poisson}(E_i; \theta_i) \text{ (equation 1)}$$

$$\log(\theta_i) = \alpha + \beta_{xi} + s_i \text{ (equation 1.1)}$$

where α is an intercept representing the average number of deaths across the 4050 parishes, and β_{xi} denotes the effect of socioeconomic deprivation. The area-specific effect s_i was modelled using a Besag, York and Mollié (BYM) model (33), with the parameterization proposed by Dean and colleagues (34) (Eq. 1.2).

$$s_i = \tau (\sqrt{\varphi * u_i} + \sqrt{1 - \varphi * v_i}) \text{ (equation 1.2)}$$

where u_i represents the structured spatial effect and v_i the unstructured effect. The u_i effect was scaled to enhance model interpretability (35), such that u represents the proportion of the spatial effect attributable to the structured component, and $1/s$ corresponds to the marginal variance of s_i . An adjacency-based criterion was used to construct the spatial weights matrix, except for isolated geographical areas (islands), where a distance-based criterion was applied. Specifically, when an area had no adjacent neighbours, the geographically closest area was considered its neighbour.

Associations were expressed as relative risks (RRs), representing the ratio between the risk of death in each deprivation quintile and that of the reference quintile (the least

deprived, quintile 1). An RR was considered significantly higher or lower when its 95% credible interval (95% CrI) did not include value 1. RRs and 95% CrIs were derived from posterior means and quantiles. Posterior distributions were obtained using the Integrated Nested Laplace Approximation (INLA), implemented through the R-INLA package (36).

3. RESULTS

3.1. Step 1: Construction of the individual deprivation indicator

Selection of fundamental needs

The selection of fundamental needs was based on the thirteen candidate items available in the EU-SILC 2021 survey. All fundamental needs were included (n=12) except ‘Regularly participate in a leisure activity’, as more than 50% of individuals could not afford it; therefore, this variable was removed from further analysis (Table 1). These items reflected contemporary material and social living conditions and were evaluated for their association with both objective and subjective poverty.

Table 1. Identification of fundamental needs: proportion of Portuguese individuals that indicated that specific goods and services were not within their means (EU-SILC survey 2021, n=26,822).

Fundamental needs	% of households that cannot afford
Eat a meal containing some meat or some fish or the vegetarian equivalent once every two days	2.6
One-week annual holiday away from home	38.2

Use your own means to cover a necessary yet unplanned expense of €800	31.4
Keep home adequately warm	17.5
Have a computer	5.9
Have a car	5.2
Replacing worn-out furniture	38.7
Replacing worn-out clothes by some new	8.6
Two pairs of properly fitting shoes	1.1
Get-together with friends/family for a drink/meal at least once a month	7.2
Spend a small amount of money each week on yourself	12.3
Internet connection for personal use at home	3.4

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344 **Identification of fundamental needs associated with poverty**

345 Among the twelve candidate needs considered, seven items were significantly associated
346 with both objective and subjective poverty and were therefore retained as fundamental
347 needs in the construction of the individual deprivation indicator (Table 2). The retained
348 fundamental needs included the capacity to cover unexpected financial expenses, the
349 ability to take a one-week annual holiday away from home and to to keep home
350 adequately warm, having a car, the possibility of replacing worn-out furniture, replacing
351 worn-out clothes with new ones, and the capacity to spend a small amount of money
352 weekly on oneself.

353

354 Table 2. Associations between each fundamental need and both objective and subjective
355 poverty (EU-SILC survey 2021, n=23,082).

	Objective poverty	Subjective poverty
	OR (95% CI)	OR (95% CI)
Use your own means to cover a necessary yet unplanned expense of €800*	1.831 (1.589 - 2.110)	4.564 (3.969 - 5.248)
One-week annual holiday away from home*	1.943 (1.678 - 2.251)	1.788 (1.537 - 2.080)
Have a computer	0.972 (0.790 - 1.195)	1.401 (1.148 - 1.710)
Eat a meal containing some meat or some fish or the vegetarian equivalent once every two days	1.309 (1.002 - 1.710)	1.180 (0.896 - 1.554)
Keep home adequately warm*	0.836 (0.718 - 0.973)	1.456 (1.260 - 1.682)
Have a car*	1.864 (1.485 - 2.340)	1.385 (1.077 - 1.781)
Replacing worn-out furniture*	1.576 (1.349 - 1.841)	2.611 (2.237 - 3.046)
Replacing worn-out clothes by some new*	1.355 (1.117 - 1.644)	1.950 (1.604 - 2.372)
Two pairs of properly fitting shoes	1.020 (0.616 - 1.690)	1.674 (1.003 - 2.796)

Get-together with friends/family	1.076	1.366
for a drink/meal at least once a month	(0.876 - 1.322)	(1.117 - 1.671)
Spend a small amount of money each week on yourself*	1.577 (1.326 - 1.875)	1.817 (1.512 - 2.185)
Internet connection for personal use at home	1.275 (0.998 - 1.631)	1.171 (0.886 - 1.549)

*fundamental needs associated with both objective and subjective poverty; Bold denotes statistically significant associations

Definition of the individual deprivation threshold

A binary individual deprivation indicator was defined based on the number of unmet fundamental needs resulting from financial incapacity. Multivariable logistic regression models were used to determine the threshold number of unmet needs that best predicted both objective and subjective poverty.

The optimal threshold corresponded to lacking at least two fundamental needs. Using this threshold within the twelve-needs framework, approximately 39.6% of individuals were classified as deprived, indicating a substantial prevalence of deprivation within the Portuguese population.

3.2. Step 2: Selection and dichotomization of shared variables

A set of 16 variables common to both the EU-SILC survey and the Portuguese census was identified to enable translation of individual-level associations into ecological-level indicators.

The candidate shared variables included demographic characteristics such as sex, age group, marital status, citizenship, and country of birth, as well as socioeconomic variables including educational attainment, employment status, occupational class, and housing characteristics. Additional variables related to household structure, including number of rooms, tenure status, rent value, household size, and household composition, were also included.

The dichotomization process identified optimal thresholds for each variable. These dichotomized variables were subsequently used as ecological indicators in the multivariable modelling stage. The variables, along with their original coding and optimal dichotomization, are presented in Additional file 1.

3.3. Step 3: Construction of the ecological deprivation index

Selection of variables for the final model

A multivariable logistic regression model was fitted using the individual deprivation indicator as the dependent variable and the candidate shared variables as independent variables. Variables that remained significantly associated with individual deprivation were retained in the final ecological model, as presented in Table 3.

Table 3. Final model of multivariable logistic regression selecting components of EDI, which were associated with the final individual deprivation indicator, Portuguese EU-SILC.

Variable	Regression coefficient (95% CI)	OR (95% CI)
Proportion of individuals not married	0.50 (0.35 – 0.65)	1.65 (1.42 – 1.92)
Proportion of foreign-born individuals	0.39 (0.14 – 0.64)	1.48 (1.15 – 1.90)
Proportion of individuals with low educational attainment (up to 3rd cycle basic education)	0.89 (0.73 – 1.04)	2.43 (2.08 – 2.83)
Proportion of non-employed individuals	1.03 (0.25 – 1.82)	2.81 (1.29 – 6.16)
Proportion of individuals in non- professional/managerial occupations (ISCO 3–9)occupations (ISCO88 groups 3 to 9)	1.50 (1.30 – 1.71)	4.50 (3.67 – 5.52)
Proportion of dwellings with<5 rooms	0.31 (0.16 – 0.47)	1.37 (1.18 – 1.59)
Proportion of tenant-occupied dwellings	0.66 (0.45 – 0.87)	1.93 (1.56 – 2.38)
Proportion of large households (≥5 persons)	0.66 (0.44 – 0.89)	1.94 (1.55 – 2.43)
Proportion of households not composed of couples with children aged <25 years	0.19 (0.04 – 0.33)	1.20 (1.04 – 1.40)

ISCO-88 (International Standard Classification of Occupations, 1988)

Regression coefficients were used as weights in constructing the ecological deprivation index, with their magnitude indicating each variable's contribution to deprivation. Non-

professional/managerial occupations (ISCO 3-9), non-employment, low education, household size, and tenant status showed the strongest associations. Hence the final equation (equation 2) of the EDI-PT was the following:

$$\begin{aligned} EDI - PT \ 2021 = & 0.50P_{not\ married} + 0.39P_{foreign\ born} + 0.89P_{low\ education} + \\ & 1.03P_{non\ employed} + 1.50P_{non-professional/managerial\ occupations\ (ISCO\ 3-9)} + \\ & 0.31P_{\geq 5\ rooms} + 0.66P_{tenants} + 0.66P_{large\ households\ (\geq 5\ rooms)} + \\ & 0.19P_{households\ not\ composed\ of\ couples\ with\ children\ aged\ <25\ years} \end{aligned} \quad (\text{Equation 2})$$

3.4. EDI-PT descriptive statistics and geographic distribution

The EDI-PT showed the following distribution: minimum= −10.946; maximum=13.637; mean=0.000; and standard deviation=2.800. Census block groups were categorized into deprivation quintiles using the EDI-PT score as cut-offs: 1 (−10.946 to −2.013); 2 (−2.013 to −0.320); 3 (−0.320 to 0.812); 4 (0.812 to 2.078); and 5 (2.078 to 13.637). The first quintile (least deprived) comprised 2,375,762 inhabitants (23.0% of the population); the second, 2,267,585 (21.9%); the third, 2,126,541 (20.6%); the fourth, 1,886,936 (18.2%); and the fifth (most deprived), 1,686,242 (16.3%).

The spatial distribution of the EDI-PT, shown in Figure 1, revealed marked geographical inequalities across Portugal. Overall, the maps reveal clear geographic variation across all geographical scales, with marked territorial inequalities across the country. Higher values of socioeconomic deprivation are predominantly observed in southern and inland areas, particularly across parts of Alentejo, Algarve, Azores and Madeira. In contrast, lower values tend to be concentrated along the northern and central coastal corridor, including areas surrounding the metropolitan regions of Porto and Lisbon.

3.5. Association between deprivation and mortality

The association between socioeconomic deprivation and all-cause mortality was examined using hierarchical Bayesian spatial models, and the results are shown in Table 4.

At the parish level analysis, compared with areas in the least deprived quintile (Q1), areas in higher deprivation quintiles exhibited progressively increased relative risks of mortality. This gradient suggested a dose-response relationship between deprivation and mortality. Sensitivity analyses conducted at the municipality scale demonstrated the same direction and magnitude of associations between deprivation and mortality.

Table 4. Association (Relative Risk and 95% Credible Intervals) between the European Deprivation Index quintiles (Q1-least deprived to Q5-most deprived) and age-adjusted mortality rates in Portugal (n=3092 parishes and n=308 municipalities, 2019-2022).

Quintile of socioeconomic deprivation	Relative Risk (95% Credible Intervals)	Relative Risk (95% Credible Intervals)
Scale	Parish level	Municipality level
Q1-least deprived	1.000 (Reference category)	1.000 (Reference category)
Q2	1.034 (1.016-1.052)	1.001 (0.965-1.038)
Q3	1.055 (1.034-1.074)	1.048 (1.010-1.088)
Q4	1.068 (1.047-1.090)	1.056 (1.017-1.096)
Q5-most deprived	1.090 (1.067-1.115)	1.103 (1.062-1.145)

Bold denotes statistically significant associations.

These findings indicate that mortality risk increased with increasing deprivation level, supporting the validity of the EDI-PT 2021 as a measure of socioeconomic inequalities in health.

4. DISCUSSION

The present study describes the development of the updated Portuguese version of the European Deprivation Index for 2021 (EDI-PT 2021), constructed using an expanded framework based on thirteen candidate fundamental needs and applied across multiple spatial scales. The results demonstrate that the updated index captures multidimensional patterns of socioeconomic deprivation and shows a consistent positive association with all-cause mortality. These findings support the validity of the EDI-PT 2021 as a robust indicator of territorial socioeconomic inequalities and reinforce its relevance for epidemiological research and public health planning.

A key methodological contribution of this study lies in the adoption of an expanded set of candidate fundamental needs reflecting contemporary living standards. Previous versions of the Portuguese European Deprivation Index relied on a smaller set of needs that primarily captured traditional aspects of material deprivation. The introduction of the thirteen-needs framework represents an important methodological evolution, incorporating dimensions related not only to basic consumption but also to social participation and household resilience. Compared with the 2011 version of the Portuguese European Deprivation Index (EDI-PT), the 2021 version reflects an important evolution in the conceptualization of deprivation by incorporating a broader and more contemporary set of fundamental needs. In 2011, the index was based on nine candidate material deprivation items available in the EU-SILC survey, of which six were retained as fundamental needs after testing their association with objective and subjective poverty:

the ability to eat meat/fish regularly, cover unexpected expenses, keep the home adequately warm, have a phone, have a washing machine, and have access to a car. The item “one week annual holiday away from home” was excluded because more than 50% of Portuguese households could not afford it. In contrast, the 2021 version expanded the candidate needs to thirteen items, reflecting changing social norms and living conditions, including access to the internet, replacing worn-out furniture or clothes, social participation, and spending money on oneself. Twelve items fulfilled the criterion of being affordable to the majority of the population, while “regularly participate in a leisure activity” was excluded because more than 50% of individuals could not afford it. Moreover, the 2021 version incorporated dimensions of social participation and digital inclusion that were absent in 2011, illustrating how deprivation has evolved beyond basic material conditions toward broader aspects of social integration and quality of life. The threshold of lacking at least two fundamental needs identified in this study was consistent with previous Portuguese EDI developments (6, 8). The prevalence of deprivation estimated using this threshold indicated that approximately 39.6% of individuals experienced some level of deprivation, suggesting that socioeconomic disadvantage remains a significant concern in Portugal. Although methodological differences limit direct comparisons with earlier versions of the index, the higher prevalence observed under the thirteen-needs framework likely reflects the broader conceptualization of deprivation rather than a simple increase in poverty levels. The expanded framework improves sensitivity to subtle forms of disadvantage that may not be captured by more restricted definitions of deprivation. Nevertheless, it is important to highlight that the index was replicated using the six fundamental needs included in the original version, and a very high correlation ($\rho > 0.924$, $p < 0.001$) was observed between census tract deprivation levels derived from both versions. This finding suggests that the

methodological modification does not meaningfully affect the spatial distribution of deprivation.

The selection of shared variables linking individual-level deprivation to ecological-level indicators revealed strong associations between deprivation and core socioeconomic characteristics. Variables related to education, employment status, occupational class, and housing conditions remained central components of the final model. These findings are consistent with well-established literature demonstrating the role of labour market participation, educational attainment, and housing stability as key determinants of socioeconomic disadvantage (37, 38).

It is important to note that substantial differences between the 2011 and 2021 versions of the EDI-PT were also observed in the ecological variables included in the weighted sum used to construct the final deprivation index. The 2011 EDI-PT included eight weighted census variables: non-owned households, households without indoor flushing, households with five rooms or less, blue-collar occupations, low education, non-employers, unemployment, and foreign residents. These variables primarily captured traditional forms of material deprivation and housing inadequacy. In the 2021 version, the final model included nine variables: proportion of individuals not married, foreign-born individuals, low educational attainment, non-employed individuals, non-managerial/professional occupations, dwellings with fewer than five rooms, tenant-occupied dwellings, large households, and households not composed of couples with children under 25 years. Compared with the 2011 version, indicators related to severe housing deprivation (e.g., absence of indoor flushing) disappeared, reflecting improvements in housing conditions in Portugal (39) over the last decade (going even further back, the 2001 version, besides the absence of indoor flushing, still included the absence of bath or shower); these variables are actually no longer collected in the census.

Simultaneously, new variables linked to household composition and marital status, suggesting that contemporary deprivation increasingly reflects family structures rather than extreme material deprivation alone.

The spatial distribution of deprivation identified in this study revealed marked geographical heterogeneity across Portugal. Although detailed mapping results are presented in separate publications, the observed spatial patterns confirmed the existence of regional clusters of deprivation that align with historically disadvantaged territories, already observed in previous versions of the EDI (6, 8) and other previous studies on the geographies of material deprivation in Portugal (40). Such spatial gradients reflect longstanding territorial inequalities influenced by structural economic differences, demographic ageing, and regional disparities in employment opportunities (40, 41). The stability of these patterns across spatial scales suggests that deprivation remains geographically embedded and that localized interventions are required to address area-level inequalities and discontentment in these areas (42). This persistence in the spatial pattern of deprivation has been observed elsewhere (43, 44). For instance in the UK, in London, the maps of poverty in 1800s, 1900s and 1990s are quite similar and these patterns match the distribution of key health outcomes such as mortality (43).

The association between deprivation and mortality observed in this study reinforces the validity of the EDI-PT 2021 as a meaningful measure of population vulnerability. Areas classified in higher deprivation quintiles exhibited progressively higher mortality risks compared with the least deprived areas, indicating a clear dose-response relationship between socioeconomic disadvantage and health outcomes. This gradient is consistent with extensive epidemiological evidence linking socioeconomic conditions to mortality (6, 9) and supports the continued use of deprivation indices as tools for identifying health inequalities (4).

Importantly, the consistency of deprivation-mortality associations across multiple spatial scales demonstrates the robustness of the EDI-PT 2021. Analyses conducted parish, and municipality levels yielded similar patterns of association, suggesting that the index performs reliably across different levels of geographical aggregation, with no evidence of MAUP at least for these two levels of analysis. This multi-scale applicability enhances the usefulness of the index for both local and national public health planning, enabling policymakers to tailor interventions according to the scale of decision-making.

A key strength of this study lies in the use of harmonized European data sources combined with exhaustive national census information. The integration of EU-SILC and census data ensures both methodological rigor and national representativeness, allowing the derivation of small-area deprivation measures applicable across the entire country. The use of standardized procedures also facilitates comparison with deprivation indices developed in other European countries, supporting cross-national research on socioeconomic inequalities.

Despite previously mentioned strengths, several limitations should be acknowledged. First, the use of aggregated ecological indicators may introduce ecological bias, as individual-level associations cannot be directly inferred from area-level measures (45). Although the EDI is designed to approximate individual deprivation at the population level, residual heterogeneity may exist within spatial units. Second, as with any area-based measure, results may be influenced by the Modifiable Areal Unit Problem, whereby analytical outcomes vary according to the scale and boundaries of spatial aggregation (46). Although sensitivity analyses across multiple spatial levels suggest stable results, caution is warranted when interpreting geographical comparisons. Another limitation relates to the availability and comparability of variables across data sources. The construction of the EDI requires variables that are present in both individual-level and

census datasets, potentially limiting the inclusion of certain relevant socioeconomic dimensions. Additionally, although mortality data were aggregated to improve statistical stability, temporal aggregation may mask short-term fluctuations in mortality patterns. Future research should explore the application of the EDI-PT 2021 in the analysis of specific health outcomes beyond all-cause mortality, including chronic disease incidence, mental health outcomes, and health service utilization. The integration of deprivation indicators with environmental and urban characteristics may also provide valuable insights into the interplay between social and physical determinants of health. Furthermore, periodic updates of the index will be essential to ensure that deprivation measures remain aligned with evolving societal conditions and technological developments.

From a policy perspective, the updated EDI-PT 2021 provides an essential tool for identifying vulnerable populations and guiding targeted interventions. The ability to detect deprivation at small geographical scales allows policymakers to allocate resources more efficiently and design place-based strategies aimed at reducing health inequalities. The use of deprivation indices in public health surveillance can also support monitoring of social progress and evaluation of policy effectiveness over time.

5. CONCLUSION

In conclusion, the development of the Portuguese European Deprivation Index 2021 represents an important advancement in the measurement of socioeconomic deprivation. By incorporating an expanded framework of fundamental needs and demonstrating consistent associations with mortality across multiple spatial scales, the EDI-PT 2021 provides a sensitive and reliable indicator of territorial inequalities. The updated index is expected to serve as a valuable resource for epidemiological research, public health

planning, and policy development aimed at reducing socioeconomic inequalities and improving population health.

Availability of data and materials

The datasets used and/or analyzed during the current study are described in the Methods section of the manuscript. All data are publicly available from the cited sources therein. The final 2021 Portuguese version of the European Deprivation Index (EDI-PT 2021) is publicly available at: <https://zenodo.org/records/20442446>.

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Author contributions: CRediT

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FIGURE LEGENDS

Figure 1. Spatial distribution of the European Deprivation Index for Portuguese small-areas in Continental Portugal (A: Census block groups; B: Parishes; C: Municipalities).

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Figures

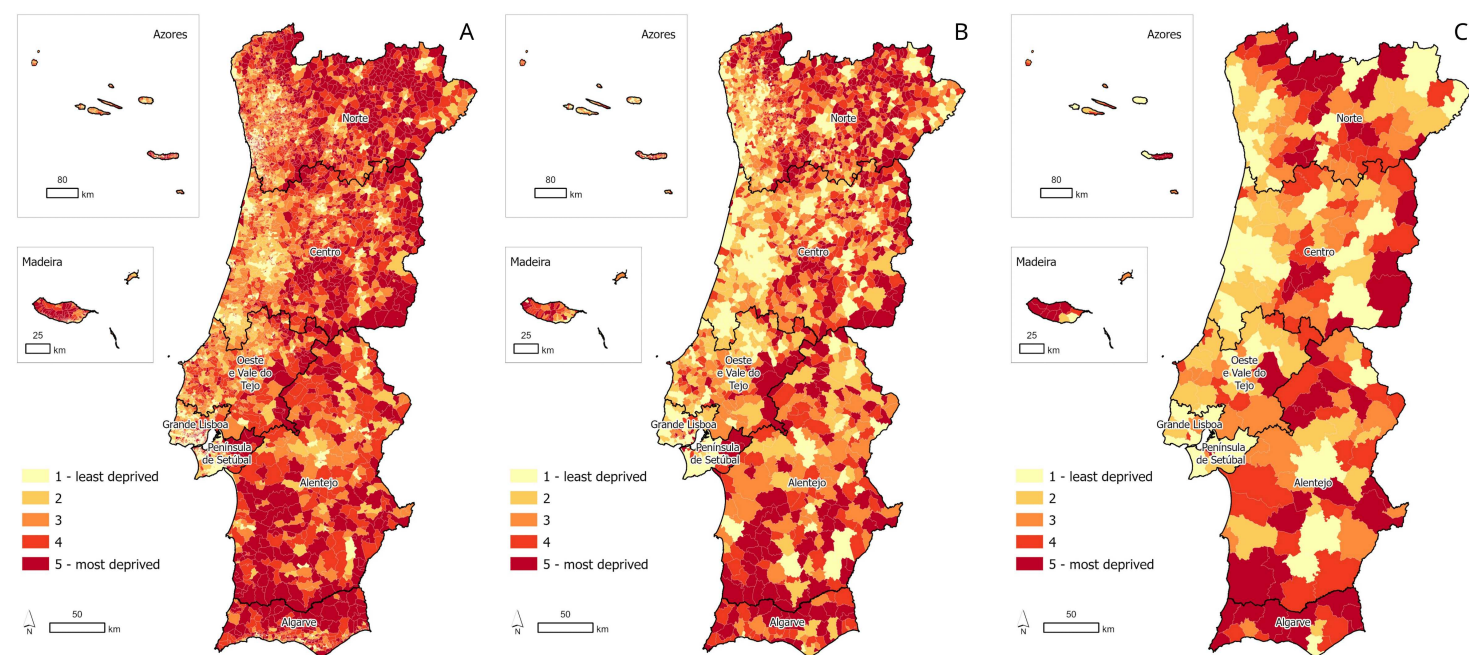


Figure 1

Spatial distribution of the European Deprivation Index for Portuguese small-areas in Continental Portugal (A: Census block groups; B: Parishes; C: Municipalities).

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