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Socioeconomic, Environmental, and Digital Determinants of Life Expectancy in Andorra: A Comparative Analysis with EU and EFTA Countries

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Running title:

Longevity in Andorra: A European Comparison

ABSTRACT

Background

European life expectancy is driven by complex socioeconomic, environmental, and digital determinants. This ecological study provides a macro-regional assessment of European longevity across 32 nations (EU27, EFTA, and Andorra), establishing an optimized predictive framework to isolate key structural drivers of population lifespans, with a specific focus on the unique sociodemographic position of the Principality of Andorra.

Methods

Utilizing a 5-year post-pandemic dataset (2020–2024), feature selection was conducted via LASSO regression paired with variance inflation factor diagnostics to eliminate severe multicollinearity. An optimized multivariate ordinary least squares regression model was fitted to identify independent structural predictors of life expectancy. Additionally, Hierarchical Cluster Analysis using Ward's minimum variance method was applied to classify nations based on shared socioeconomic and demographic profiles.

Results

This research reveals a novel, previously undescribed statistical relationship correlating country-level digital literacy indicators to extended life expectancy. The optimized multivariate ordinary least squares model explained 95.9% of cross-national longevity variance (adjusted $R^2 = 0.959$). The super-aging index demonstrated the strongest positive association with life expectancy, whereas a widening sex-specific longevity gap and ambient sulfur dioxide pollution presented the primary negative constraints. Andorra occupies the leading edge of this health landscape, sustaining a 5-year stationary mean life expectancy of 83.68 years (behind only Switzerland and Liechtenstein), while Andorran women achieve the highest life expectancy at birth across the European continent (86.20 years). Territorially, Andorra exhibits unique sociodemographic characteristics: while its low environmental emissions, high labor participation, and digital assets act as effective public health safeguards, baseline data reveal elevated income inequality

alongside record-low demographic dependency ratios. Hierarchical Cluster Analysis further demonstrates that European small nations share a cohesive regional branch defined by unique scale-related structural profiles, suggesting that small nations can offer vital paradigm models for optimized health infrastructure.

Conclusions

European longevity is driven by demographic expansion and air quality. In addition, country digital literacy is newly correlated to extended population lifespans. Microstates like Andorra, at the forefront of European longevity, leverage scale-related structural advantages and specifical challenges. Small nations offer vital paradigm models for optimized health infrastructure.

KEYWORDS

Life expectancy, Andorra, Longevity, Digital literacy, Super-aging index, Air pollution, Small nations, Ecological study

BACKGROUND

Modern public health aims not only to prolong the duration of life but to improve its quality, reducing suffering and fostering a state of complete physical, mental, and social well-being [1,2]. This objective is encapsulated in the World Health Organization's (WHO) redefinition of healthy ageing, which focuses on maintaining the functional ability that enables well-being in older age. Functional ability is determined by the interaction between an individual's intrinsic capacity, including composite physical and mental strengths, and the social and physical environments they inhabit. It has been argued that living longer and experiencing good health are independent but equally essential milestones for human development policies [3]. A robust public health system serves as a crucial driver for national progress, as a healthy population acts as a catalyst for economic development [4]. Within this framework, life expectancy at birth remains a fundamental synthetic indicator that objectively reflects the overall viability of a population, the effectiveness of its healthcare infrastructure, and the socioeconomic conditions of its environment [4,5].

Life expectancy at birth is the standard indicator used to measure a population's living and health conditions, representing the average number of years a newborn is expected to live if existing mortality patterns remain constant [6]. It is calculated using demographic life tables based on age-specific mortality rates, which are typically derived from vital statistics registries and population censuses [7]. Before the COVID-19 pandemic, European life expectancy improvements slowed notably around 2011. However, those nations that afterwards maintained progress in life expectancy through reduced cardiovascular and neoplasm mortality demonstrated greater resilience during the COVID-19 pandemic. Government policies addressing risk factors like harmful diets and physical inactivity are essential for building population resilience against future shocks [8].

The reliability of life expectancy can be compromised by temporary mortality shocks, such as the COVID-19 pandemic, which caused unprecedented global declines in longevity that have been slow to recover in many regions [9]. This statistical fragility is particularly acute in small-scale populations, such as microstates or local administrative areas, where a low absolute number of registered deaths leads to high variability and instability in mortality rates [10]. In these contexts, traditional estimation methods often face calculation difficulties and carry potential errors, making the resulting figures less stable and harder to compare internationally. Consequently, smoothing techniques are essential for improving age-specific mortality profiles in areas with limited data [6]. Other strategies include data aggregation, either through multiannual averages or by pooling geographically contiguous areas. These methods allow the identification of persistent longevity patterns even in small territories like Andorra, where survival rates have historically been high [3].

Population longevity operates as a multidimensional parameter where social, environmental, and, emergingly, digital determinants interact [4,11]. Unfavorable social determinants of health, such as low education attainment, unemployment, poor working conditions, and family instability, are associated with poorer health outcomes [5]. Economic prosperity, often measured through gross national income and gross domestic product (GDP) per capita, remains one of the strongest predictors of life expectancy, showing a significant positive correlation with survival years [4]. However, this relationship is non-linear; at higher income levels, a phenomenon of demining returns is observed, where additional wealth yields progressively smaller gains in longevity [12].

Beyond wealth, educational attainment rates are crucial positive determinants, as they facilitate access to better employment, healthier lifestyle choices, and more effective interaction with healthcare systems [13]. Health system variables also play a decisive role; higher current health expenditure and the density of medical resources, such as physicians and hospital beds, positively correlate with population health outcomes [11]. These structural benefits, however, are often counteracted by behavioral and environmental risks that show an inverse correlation with

longevity, most notably tobacco use, excessive alcohol consumption, and environmental pollution, such as carbon dioxide (CO_2) emissions and particulate matter [11]

Within the European context, although most European Union (EU) and European Free Trade Association (EFTA) countries have reached epidemiological excellence with life expectancies exceeding 80 years, significant health inequalities persist due to varying socioeconomic structures and differential exposure to environmental risks. These disparities are deeply rooted in socioeconomic determinants such as education and occupational class, which dictate not only the duration of one's career but also their healthy working life expectancy [14]. Across European nations, individual financial stability and employment status remain critical predictors of life satisfaction, a cognitive judgment that is inextricably linked to health outcomes [15].

Furthermore, environmental determinants play a dual role in this landscape; while regions with high environmental efficiency, particularly those transitioning toward service-oriented and knowledge-based economies, tend to exhibit higher life expectancy, those suffering from environmental degradation and heavy industrial land use report lower levels of wellbeing [15]. Finally, the emerging digital landscape introduces a new dimension of inequality, as access to health technologies, such as personal health records, is currently patterned by income and education [16].

Growing interest in the geographical variability of longevity has led to the identification of so-called "Blue Zones," regions characterized by an exceptional prevalence of centenarians compared to adjacent areas [17,18]. Among well-characterized Blue Zones, such as Ogliastra in Sardinia, Ikaria in Greece, and the Nicoya Peninsula in Costa Rica, a mountainous or hilly topography emerges as a recurring environmental feature. Studies in these high-mountain areas have highlighted how naturalized physical activity, such as walking daily on rugged terrain, and robust community support act as vital protective factors [17,18]. Beyond lifestyle, growing evidence suggests that residency at moderate altitudes (typically between 1,500 and 2,500 meters) is

associated with a more favorable cardiometabolic profile, including significantly lower mortality from cardiovascular diseases, coronary heart disease, and stroke [19]. This "altitude effect" may be driven by biological adaptations to moderate hypoxia, which can trigger protective mechanisms such as the activation of hypoxia-inducible factor (HIF) pathways and increased nitric oxide (NO) production, contributing to cardioprotective and neuroprotective benefits. Furthermore, recent research suggests that living at higher elevations is linked to a reduction in DNA damage-induced senescence. While increased ultraviolet (UV) radiation at these altitudes can accelerate photoaging, the overall disease burden and exposure to metabolic and behavioral risks are often lower, supporting extended life expectancy and enhanced biological resilience [19,20].

In this scenario, the Principality of Andorra, along with other microstates and small EFTA nations, is systematically at the forefront of European longevity. Demographic analyses place Andorran life expectancy at birth surpassing neighboring territories and established European baselines. Geographically, Andorra is a mountainous microstate with an average elevation of 1,996 meters and a minimum base of 840 meters. European microstates are generally characterized by high standards of living and citizen safety, alongside robust healthcare infrastructures that foster high life expectancy, although they simultaneously face unique scale-related structural constraints [21]. Andorra perfectly instantiates this framework, scoring 95 out of 100 on the Global Burden of Disease Healthcare Access and Quality Index [22].

Beyond mere statistics, these small-population nations are considered high-value "living labs" for public health research [23]. Their compact geography and unified healthcare systems allow for the analysis of governance and well-being dynamics in a more granular way than is possible in larger nations [24]. However, these microstates also navigate specific vulnerabilities, such as a dependency on larger neighboring countries for specialized expertise and a susceptibility to cross-border transmission dynamics, which was prominently highlighted during the COVID-19 pandemic [25].

Despite Andorra's high longevity statistics, a gap still exists in scientific knowledge regarding which specific multivariate configuration, including digital competence and post-pandemic inequalities, sustains this exceptional longevity compared to its European and EFTA counterparts. Therefore, this study evaluates the multidimensional profiles influencing longevity in the Principality of Andorra in comparison with those of EU and EFTA countries. Specifically, the interaction between localized socioeconomic, environmental, digital factors and population longevity is examined to identify actionable metrics that, if structurally modified, could hold the greatest potential to continuously safeguard and sustain high life expectancy in the territory.

MATERIAL AND METHODS

Study design

This is a descriptive, comparative and ecological study designed to analyze socioeconomic, environmental, and digital determinants of life expectancy in Andorra compared to those of the European Union (EU) countries (Belgium, Bulgaria, Czechia, Denmark, Germany, Estonia, Ireland, Greece, Spain, France, Croatia, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Hungary, Malta, Netherlands, Austria, Poland, Portugal, Romania, Slovenia, Slovakia, Finland and Sweden) and the EFTA countries (Iceland, Liechtenstein, Norway and Switzerland). The study period covers the post-pandemic context from 2020 to 2024, using 5-year longitudinal data to determine both stationary structural profiles (means) and longitudinal dynamics (trends). The sample used in this study includes data from 32 countries, although availability for specific variables was subject to data restriction constraints in some EFTA territories. Longitudinal trends were calculated when data were available within the 5-year analyzed period.

Data sources

Data for Andorra were primarily obtained from the Department of Statistics of the Government of Andorra [26] while environmental and air quality indicators were collected by the Ministry of Environment, Agriculture and Livestock of the Government of Andorra [27]. Comparative European data were retrieved from Eurostat [28] and the European Environment Agency (EEA) [29].

Variables and measures

The study analyses 31 key indicators categorized into seven dimensions: demographics and gender, dependency and aging, poverty and inequality, education and economic prosperity, emissions and air quality, digital literacy and quality of life (**Table 1**). These variables were selected based on their established relationship with health or life expectancy, provided they were collected in Andorra using methodologies compatible with those of Eurostat or EEA standards

241 for the 2020-2024 period. Indicators not recorded in Andorra or those utilizing non-comparable
242 methodologies were excluded to ensure statistical consistency.
243
244 **Statistical analysis**
245 Exploratory analysis
246 The study analyzed both stationary profiles (5-year means) and longitudinal dynamics (annual
247 trends). Annual trends were derived from the slope of linear regressions over the 5-year period.
248 The relationship between life expectancy and 30 socioeconomic, environmental, and digital
249 indicators was initially assessed using Pearson correlation coefficients (r).
250 Variable selection and multicollinearity diagnostics
251 Given the high dimensionality of the dataset and the presence of correlated predictors, traditional
252 linear models were deemed suboptimal due to risks of overfitting and multicollinearity. A least
253 absolute shrinkage and selection operator (LASSO) regression was first performed to select the
254 most relevant predictors, with the penalty parameter (λ_{min}) determined via k-fold cross-validation.
255 An ordinary least squares (OLS) model was then fitted using only the variables selected by
256 LASSO. Variance Inflation Factor (VIF) diagnostics were applied to this final OLS model to
257 ensure no residual multicollinearity existed among the selected predictors (threshold <5).
258 Multivariate modelling
259 A multiple linear regression (OLS) model was constructed using the optimized subset of
260 predictors. The model's goodness-of-fit was evaluated using the adjusted R^2 and F-statistic. The
261 Gauss-Markov assumptions were verified through a comprehensive residual diagnostic panel,
262 including: residuals vs. fitted plots for linearity and homoscedasticity, normal quantile-quantile
263 (Q-Q) plots for error distribution normality, scale-location plots for variance stability and Cook's
264 distance to detect influential outliers.
265 Cluster analysis
266 To identify territorial groupings, a hierarchical cluster analysis (HCA) was then conducted using
267 Ward's minimum variance method (Ward.D2) based on a Euclidean distance matrix. To avoid
268 structural distortions and ensure equal weighting, all predictors, restricted to the optimized post-

LASSO/VIF predictor subset, were standardized via Z-score transformation. For non-hierarchical grouping, clustering was performed, with the optimal number of clusters determined by a consensus majority rule across 30 statistical indices using the NbClust package in R [30].

A comparative socioeconomic, environmental and digital heatmap was constructed. Territories were arranged horizontally in descending order of global life expectancy to facilitate the identification of structural patterns associated with longevity. The visualization used a divergent color palette centered at zero, with a fixed symmetric scale ranging from -2 to +2 to highlight deviations from the European mean.

All statistical analyses were performed using R software version 4.5.3. Statistical significance (p-value) was meant as follows: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

RESULTS

Baseline and longitudinal trajectory of Andorran life expectancy

The longitudinal analysis of global life expectancy at birth between 2020 and 2024 reveals that Andorra consistently occupies a top position within the European health landscape. Andorra's 5-year stationary mean stands at 83.68 years, ranking third absolute out of the 32 analyzed countries, only surpassed by Switzerland (83.90 years) and Liechtenstein (83.78 years), and positioning above Spain (83.36 years) and Sweden (83.22 years).

While the lowest European Union bounds dropped significantly during the health crisis, Andorra tracked closely along the maximum EFTA and EU ceilings, represented by Switzerland and Spain, respectively (**Figure 1**). Furthermore, Andorra exhibits a strong positive annual trend (β = 0.41 years/year) that matches Spain's growth pace and outperforms Switzerland (β = 0.32 years/year), being outpaced only by Liechtenstein (β = 0.50 years/year). Collectively, these longitudinal metrics demonstrate that Andorra experienced a robust post-pandemic recovery in its life expectancy predictions.

When analyzing sex-specific differences (**Figure 2**), all 32 countries fall strictly above the 1:1 identity line, confirming a higher life expectancy for women across the board. Andorra showcases a 5-year mean life expectancy of 86.20 years for women and 81.06 years for men, resulting in a gender gap of 5.14 years. Remarkably, Andorran women exhibit the highest life expectancy at birth in Europe (86.20 years), followed by Spain (86.08 years) and Switzerland (85.72 years). Graphically, Andorra situates closely with other high-longevity European nations like Spain, Switzerland, and Liechtenstein, while remaining tightly independent of the extreme gaps observed in Eastern European states (**Figure 2**). In these states, life expectancy gender discrepancy exceeds 7 to 8 years, although recent 5-year longitudinal data suggest a contracting trend. In contrast, Andorra's annual life expectancy gender gap is dynamically shrinking at a rate of -0.19 years per year ranking 30th out of 32 countries (**Supplementary Table 1**).

A detailed screening of Andorra's baseline profiles across the extreme tail distributions (**Supplementary Table 1**) reveals a socioeconomic paradox, where exceptional structural

strengths directly coexist with critical vulnerabilities. On the highly favorable end, Andorra ranks second lowest among European territories for greenhouse gas emission profile (2.77 tons per capita). This protective baseline is reinforced by a minimal low work intensity rate (1.66%), indicating a highly active labor market. Conversely, Andorra displays critical imbalances regarding wealth distribution ranking second absolute in the European 5-year mean Gini coefficient (35.10) and presenting the highest European annual trend of Gini expansion (1.45 per year), demonstrating a post-pandemic acceleration of income inequality. Demographically, these profiles run parallel to a highly compressed femininity index (94.57 women per 100 men, bottom 2/32), underscoring a highly masculinized population structure that coexists with the lowest global, old-age, and youth dependency ratios across the analyzed European territories.

Bivariate correlations: identifying initial associations

The Pearson correlation analysis (*r*) evaluated the linear relationship between global life expectancy and the analyzed indicators regarding demographics and gender, dependency and aging, poverty and inequality, education and economic prosperity, emissions and air quality, digital literacy and quality of life (**Table 2**). Out of the significant indicators, digital intensity displayed the strongest positive linear association with longevity, followed closely by recent happiness levels, internet utilization, and GDP per capita. Significant positive correlations were also confirmed for the super-ageing index, structural infrastructure such as e-Government, e-Health/telemedicine utilization and tertiary education rates.

Conversely, significant severe negative linear correlations were detected between life expectancy and the female-male longevity gap, femininity index, upper-secondary education levels, and environmental air pollution via sulfur dioxide and particulate matter 2.5 μm ($PM_{2.5}$). Poverty frameworks like severe material and social deprivation, relative poverty, severe poverty, population at risk of poverty, income inequality and the multi-component at risk of poverty or social exclusion (AROPE) index also demonstrated significant negative linear associations (**Table 2**).

Feature selection and multicollinearity diagnostics

Given the structural overlap among socioeconomic and digital frameworks, LASSO regression was used to promote parsimony by shrinking non-influential metrics toward zero. The regularization process filtered the initial indicator matrix down to 9 critical structural predictors (**Table 3**), retaining factors as the life expectancy gender gap (β = -0.617), super-aging index (β = 0.465), and sulfur dioxide pollution (β = -0.169).

Post-LASSO VIF diagnostics revealed severe multicollinearity centered at the AROPE index (VIF = 11.64). Following a stepwise elimination protocol, the removal of the AROPE index successfully stabilized the matrix. All remaining 8 independent structural variables safely stabilized below the conservative mathematical threshold of VIF < 5.0, with severe material and social deprivation dropping from VIF = 6.18 to 3.37, confirming complete statistical independence for the multivariate regression phase (**Table 4**).

Multivariate determinants of European longevity

A multiple linear regression (OLS) model was fitted using the subset of predictors selected by LASSO and validated for multicollinearity via VIF diagnostics. The model demonstrated a high goodness-of-fit, explaining 95.9% (adjusted R^2 = 0.959) of the variance in life expectancy across the studied territories (**Table 5**). The underlying Gauss-Markov assumptions were validated via a four-panel residual diagnostic framework (**Supplementary Figure 1**), showing homoscedastic residual distributions, strict error normality on the Q-Q projection, and no influential outliers breaching Cook's distance limits.

According to our model, the super-aging index shows the highest positive significant association with global longevity (*b* = 0.49). In contrast, significant independent negative constraints on life expectancy were confirmed for the sex-specific life expectancy gap (*b* = -0.59), ambient concentration of sulfur dioxide (*b* = -0.21), the femininity index (*b* = -0.11), lower secondary to upper-secondary education levels 3 and 4 (*b* = -0.07), and active e-Health/telemedicine (*b* = -0.02). Conversely, severe poverty at the 40% threshold (*b* = -0.14) and severe material and social

deprivation (b = -0.08) appear to contribute to the overall explanatory power of the model through an inverse relationship with life expectancy, but did not reach statistical significance (**Table 5**).

Advanced multivariate country groupings

The standardized comparative heatmap, where territories are ordered by overall life expectancy, clarifies the structural vectors driving Andorra's high position (**Figure 3**) and mirrors the statistical weights identified in the multiple linear regression model. Andorra's structural profile is defined by highly specific, favorable deviations from the European baseline. Concurrently, the heatmap visually contextualizes certain anomalies that capture Andorra's unique socioeconomic profile. Andorra shows exceptionally high deployment of digital health infrastructure, with its e-Health/telemedicine usage ranking fifth out of 29 countries. This advanced digital performance, alongside the third highest life expectancy in Europe, stands in contrast to Andorra's high severe material and social deprivation, where the territory ranks sixth out of 31 countries (**Supplementary Table 2**). This highlights a characteristic epidemiological status where robust digital and health outcomes successfully coexist with negative socioeconomic variables. Demographically, Andorra displays a unique combination of a relevant life expectancy gender gap alongside a low femininity index (94.57 women per 100 men, bottom 2) and a compressed proportion of individuals at educational levels 3 and 4. Environmentally, the country appears to be protected by minimal industrial pollution footprint as indicated by low ambient sulfur dioxide (SO_2) concentrations that rank 25th out of 31 countries (**Supplementary Table 2**). This specific combination of digital integration, and exceptional air quality partially may explain why Andorra aligns with the leading edge of European longevity profiles.

To map how Andorra compares structurally within the European socioeconomic framework, a Hierarchical Cluster Analysis (HCA) using Ward's minimum variance method was applied to the optimized predictor space. The algorithm split the 32 nations into four major clusters: a lower-longevity Central/Eastern group (red), a higher-longevity Mediterranean group (blue), a Western and Nordic group (purple), and a distinct cluster of small nations (green) (**Figure 4**). Andorra is

integrated within the cluster of small countries, positioning on the shared sub-dendrogram branch alongside Malta and Luxembourg.

DISCUSSION

Previous studies have evaluated the impact of sociodemographic factors on life expectancy [31]. Life expectancy is shaped by macroeconomic factors, including GDP per capita, the Gini index, income levels, unemployment, and inflation, and healthcare infrastructure, such as the availability of facilities, the number of professionals, and public health expenditure. Furthermore, variables such as disease- and war-related mortality, smoking and vaccination rates, and environmental pollution also significantly affect these outcomes.

Our findings indicate that gender inequity negatively correlates with life expectancy, aligning with previous global analyses across 187 countries over a five-year period [32]. While traditional perspectives suggest that increasing fertility rates can influence survival discrepancies between sexes [33], our results demonstrate that a wider sex-specific longevity gap is associated with lower overall life expectancy—a pattern fully consistent with prior literature [34]. Conversely, the lower life expectancy typically observed in men is largely attributed to higher alcohol and tobacco consumption, risk-taking behaviors, and lower utilization of healthcare services rather than biological factors [34]. Consequently, structural gender inequality acts as a determinant that dampens overall health outcomes, meaning that reducing these disparities is essential to improve global life expectancy across the entire territory [35].

Although a direct correlation between the super-aging index and life expectancy has not been widely reported in previous literature, our findings reveal a statistically significant positive correlation between these two metrics. This suggests that the super-aging index, reflecting the population aged >85 relative to those aged >65, serves as a predictor of life expectancy. Interestingly, this significant relationship was not found for the aging index (ratio of individuals aged >65 to those aged <15). This distinction could mark a shift from prior research, where it was observed that the aging index responded significantly to life expectancy changes in China and the

United States of America using macro-data [36]. Other studies that exploring life expectancy within highly aged societies often do so without explicitly using the super-aging index [37,38]. Our results would indicate that in contemporary European dynamics, longevity could be more closely intertwined with the expansion of the oldest-old cohort rather than general population aging. This finding must nevertheless be approached with caution. Because the expansion of the oldest-old population inherently reflects the historical accumulation of high survival rates, the super-aging index may partially function as a consequence of sustained longevity rather than a strictly independent driver, introducing a degree of potential endogeneity or circularity.

Many population studies link the share of adults with upper secondary, post-secondary, and tertiary education to differences and trends in life expectancy, consistently finding a clear positive gradient [39]. Decomposition studies further demonstrate that shifts in educational composition toward higher percentages of tertiary education contribute substantially to rising life expectancy or quality-adjusted life expectancy [40,41]. Consistent with these findings, our analysis observed a positive correlation between tertiary education (levels 5–8) and life expectancy. Conversely, secondary and post-secondary educational levels (levels 3–4) displayed a negative correlation. Rather than indicating a detrimental effect of secondary education, this negative association could be a mathematical effect: as the expansion of higher education shifts a larger proportion of the population into tertiary levels, the relative share of individuals remaining at levels 3–4 decreases. This structural shift aligns with previous observations in the Nordic countries [40] and Australia [42], reinforcing that populations with higher educational attainment consistently experience survival advantages over those with secondary education.

Our analysis reveals a positive correlation between GDP per capita and life expectancy during the 2020–2024 period. This lines up with the hypothesis that macroeconomic prosperity remains a primary determinant of population health across European countries. Our findings align with European macro-regional literature that documents a strong wealth-longevity link, although with differences by area and period [43]. Previously, it was reported that economic factors and education

could explain up to 82.6% of life expectancy variations in the EU27 [44]. The tangible impact of economic growth in longevity was quantified in Eastern European countries [45]. Other studies show that the relationship is positive but moderate and with diminishing returns: at low levels of GDP, small increases translate into large gains in life expectancy; at high levels, very large increases in GDP are needed to increase life expectancy [46].

Several European studies link higher poverty, deprivation, and certain dependency measures to worse health, higher mortality, or fewer functional years of life [47,48]. Material and multidimensional deprivation consistently explain cross-country gaps in healthy life years and mortality, while low income and persistent poverty significantly reduce poverty-free life expectancy [49–51]. Our findings align with this consensus, as significant negative correlations between life expectancy and severe material and social deprivation, multidimensional poverty AROPE, and all income-poverty thresholds (from relative 60% to severe 40%) were obtained. Furthermore, although a direct link between low work intensity and life expectancy is not always explicit, a lack of employment would trigger poverty pathways that ultimately impact functional years and longevity [50,52]. Conversely, the literature on demographic dependency ratios shows that while population ageing increases macroeconomic and healthcare burdens, it does not imply a simple, direct negative correlation with life expectancy [53,54]. Our results align with this lack of a direct statistical link, as old-age, young-age, and global dependency ratios failed to show significant correlations with life expectancy. Taken together, these results suggest that it is the socioeconomic vulnerability and material deprivation of individuals, rather than structural demographic ratios or work intensity, that directly constrain the potential for a longer life across European populations.

Our analysis reveals a significant negative correlation between the income S80/S20 ratio and life expectancy, while the Gini coefficient shows no significant correlation. This aligns with recent evidence suggesting that standard Gini coefficient may fail to capture contemporary dynamics of health inequality, which are increasingly driven by disproportionate income gains at the very top

514 of the distribution (Sepulveda & McLaren, 2025). Although traditional research often links a
515 higher Gini coefficient directly to lower life expectancy or higher mortality [55,56], our findings may
516 highlight the importance of specific top-bottom gaps. Conceptually, the S80/S20 quintile ratio
517 effectively captures these polarization patterns, which literature connects to lower life expectancy
518 and broader longevity inequality [57].
519
520 Our results reveal a significant negative correlation between life expectancy and both $PM_{2.5}$ and
521 SO_2 levels, while no significant correlation was found with nitrogen dioxide (NO_2), greenhouse
522 gas emissions, or particulate matter 10 μm (PM_{10}). The negative relationship observed with $PM_{2.5}$
523 aligns with literature. Meeting WHO guidelines could increase longevity globally [58], and
524 removing fossil-fuel emissions could also enhance lifespan [59]. European panel data also confirms
525 that $PM_{2.5}$ exerts the largest detrimental effect among particulates (Rodríguez-Álvarez, 2021),
526 driving increased all-cause and respiratory mortality [60]. Likewise, our significant findings may
527 reinforce evidence that sulfur dioxide exposure increases mortality risk [61,62]. Conversely, our lack
528 of significance for NO_2, PM_{10} and greenhouse gases diverges from studies linking nitrogen oxides
529 [62,63] and per capita greenhouse gas emissions [64] directly to lower longevity. As suggested by
530 Rozehnalová et al. [62], these discrepancies might stem from the use of macroeconomic-level
531 aggregated data, which often dilute local variability or the conditional effects of pollutant
532 exposure in specific urban areas.
533
534 Our analysis reveals significant positive correlations between life expectancy and macro-level
535 digital indicators, including internet use, e-Government, e-Health/telemedicine, and enterprise
536 digital intensity. To our knowledge, current literature does not directly correlate these country-
537 level digital metrics with national life expectancy. Existing empirical evidence primarily links
538 digital literacy and internet or e-Health use to individual health behaviors, self-efficacy, and
539 quality of life. For instance, recent data show that higher digital literacy improves self-reported
540 health outcomes among older adults [65,66]. Furthermore, a meta-analysis established a moderate
541 positive correlation between eHealth literacy and health-related behaviors [67]. This is supported by

structural equation modeling demonstrating that digital literacy enhances quality of life in older populations, a relationship partly mediated by eHealth literacy [68]. Ultimately, while studies assert that robust digital and eHealth literacy are conceptually associated with better health, extended longevity, and reduced healthcare costs [69], our findings would provide novel macroeconomic evidence that bridges this conceptual gap by directly linking national digital advancement to population life expectancy.

Our analysis reveals significant positive correlations between life expectancy and both overall self-reported life satisfaction and recent happiness as reported by being happy "always" or "most of the time" last 4 weeks. These findings strongly align with literature linking subjective well-being to extended longevity. Specifically, a longitudinal study found that high levels of happiness and life satisfaction were associated with extended life expectancy [70]. Ultimately, robust subjective well-being is consistently associated not only with longer lifespans but also with more years lived happily [71].

Across global, national, and regional datasets, multiple linear regression is widely utilized to predict life expectancy, frequently achieving high R^2 values by integrating economic, social, and health determinants. For instance, macro-level models using global WHO data have identified mortality rates, immunization, schooling, health expenditures, and GDP as primary drivers of longevity [72], a framework mirrored in various country-specific analyses [73–75].

To position our model, we selected variables tailored to Andorra within the broader European context. In new EU27 member states, panel regressions have evaluated life expectancy against education, income inequalities, ICT use, and CO_2 emissions, notably omitting specific variables like deprivation, the femininity index, or SO_2 [76]. Furthermore, European regional analyses of years of life lost have relied on mixed models focusing on educational attainment, income, and poverty risk [77]. While existing literature covers distinct subsets of these predictors, our model uniquely unifies them into a inclusive framework.

Our multiple linear regression model isolates the independent effects of determinants, revealing key structural dynamics driving national life expectancy. However, given the sample size (n = 32) relative to the eight included predictors, these results warrant cautious interpretation regarding potential overfitting, despite an adjusted R^2 of 0.959. The super-aging index emerged as the most powerful positive predictor, suggesting that established demographic longevity structures are highly stable and resilient over time. However, this finding must be approached with caution, as the super-aging index may inherently reflect an outcome of sustained historical longevity rather than a strictly independent causative determinant, introducing a degree of potential endogeneity or circularity. Conversely, the gender life expectancy gap proved to be the strongest negative predictor (b = -0.59), suggesting that wider survival disparities between sexes severely would constrain overall population longevity. Macroenvironmental hazards, such as SO_2 pollution, also showed negative direct association with life expectancy in the multiple linear regression model. Similarly, upper secondary education (levels 3–4) shows a negative association, likely functioning as a proxy for the absence of tertiary education benefits. Finally, the model unveils vital statistical suppressions: e-Health shifted to a slightly negative relationship despite its positive bivariate correlation, and a higher femininity index aligned with lower overall life expectancy. These shifts highlight complex internal collinearities, proving that health infrastructure and demographic compositions must be evaluated within a unified macroeconomic framework rather than in isolation. Regarding socioeconomic vulnerabilities, the model suggests negative relationships for severe material and social deprivation as well as severe poverty (40%) with life expectancy. Although neither variable reached conventional statistical significance, their retention via LASSO feature selection underscores their importance to the model's overall predictive capacity, highlighting notable socioeconomic trends that warrant further investigation.

Our empirical observations regarding Andorran longevity, particularly the fact that Andorran women rank at the global forefront of life expectancy, must be interpreted through the specific structural lens of European microstates. As established in the literature, microstates like the

Principality of Andorra consistently exceed European baselines due to unique public health ecosystems characterized by exceptional standards of living, robust citizen safety, and highly accessible healthcare infrastructures [21]. While our comprehensive European regression model indicates that socioeconomic inequality generally exerts a penalty on population longevity, Andorra presents a more nuanced matrix. The territory couples higher relative social inequality metrics with world-leading lifespans. Rather than a systemic anomaly, this can be understood by examining the protective macro-environmental factors acting within this specific microstate.

The compact geography and unified healthcare governance of the principality [24] coexist with exceptionally low levels of air pollution, such as reduced SO_2 and $PM_{2.5}$ exposure, and a highly digitally integrated population proficient in e-Government and e-Health platforms. Consequently, these structural advantages appear to function as highly effective public health buffers. In small-population nations, these aggregated environmental and digital factors could mitigate or offset the conventional negative health outcomes typically predicted by socioeconomic disparities, thereby sustaining unprecedented survival advantages.

Andorra presents a unique socioeconomic profile, characterized by exceptional longevity alongside elevated income inequality metrics. Andorra ranks at the bottom for both low work intensity and greenhouse gas emissions. Because low work intensity is structurally tied to systemic poverty pathways, and greenhouse emissions directly drive hazardous ambient air pollution, Andorra's high employment rates and air quality might function as concurrent protective factors that shield population health. Conversely, Andorra's global, youth, and old-age dependency ratios, alongside its femininity index, all sit at the absolute baseline minimum. These findings must be interpreted with caution and within the country's specific demographic and labor context. Andorra features a substantial proportion of temporary, seasonal, cross-border, and newly arrived workers, and this high population mobility can influence household income measures, complicating direct comparisons with larger European nations. Furthermore, the Gini coefficient, whose baseline is elevated in Andorra, does not capture access to healthcare, public

services, employment opportunities, citizen safety, or other dimensions of well-being that can positively contribute to Andorra's health outcomes. Consequently, future studies utilizing longitudinal and population-specific data will be required to better understand how labor force composition and residency patterns shape these economic indicators.

The HCA provides critical macro-regional context to our regression model, demonstrating that European longevity can be heavily shaped by shared structural and geographic profiles. The algorithm partitioned the continent by separating lower-longevity regions from higher-longevity cohorts, isolating a distinct cluster comprised exclusively of small nations including Andorra, Malta, and Luxembourg. Andorra's strict integration within this small-country branch is consistent with the theoretical framework established by Gualtieri et al. [21], which posits that European microstates and small nations share a unique socioeconomic matrix. However, a persistent challenge in public health literature is that these small nations are frequently excluded from large-scale comparative studies due to a systematic lack of standardized, granular data. Macroeconomic models often omit microstates because their compact populations and unique scale-related structural constraints do not fit standard national reporting templates [78]. Successfully clustering Andorra alongside Malta and Luxembourg based on our optimized predictor space empirically demonstrate that these small countries emerge as a cohesive, high-value cohort. Consequently, our results highlight the necessity of generating dedicated, small-scale public health indicators, proving that these nations offer vital insights into healthcare infrastructure and longevity that can be easily omitted [79].

Several limitations must be acknowledged when interpreting the findings of this study. First, data availability was constrained to indicators systematically collected in Andorra that remained strictly comparable across the EU and EFTA regions, resulting in missing data infrastructure for specific small-scale territories and a complete lack of standardized macro-level metrics regarding healthy aging, nutrition, and physical activity. Furthermore, our analytical framework compared large nations with exceptionally small countries, a scale disparity that introduces inherent

structural asymmetries. This is compounded by a relatively small sample size (n = 32) for complex multivariate analyses, which limits statistical power and increases vulnerability to leverage points. In addition, from a mathematical perspective, life expectancy naturally exhibits an asymptotic behavior as it approaches upper biological thresholds; however, our multiple linear regression model treats it as a purely linear variable. This linear assumption creates a structural risk of overestimating the actual real-world impact of certain predictors, particularly when applied to countries displaying extreme values like Andorra. Because this study relies strictly on aggregated, country-level data, individual-level inferences cannot be made [80], nor can the model control for behavioral, genetic, or environmental factors that are not systematically observed or quantified at the national level.

To build upon this macro-level framework, future public health research must shift toward systematically analyzing longevity dynamics across European microstates. Furthermore, bridging the data gaps identified in this study will require the development of dedicated, standardized healthy aging markers within Andorra, specifically tracking nutrition, physical activity, and healthy life years. Such granular data will be vital to unraveling the precise behavioral and biological pathways that sustain unprecedented longevity within small-population countries. Given the cross-sectional nature of this ecological study, our structural observations regarding socioeconomic vulnerabilities and demographic dependency should be interpreted as hypothesis-generating. Future research utilizing longitudinal panel data or individual-level registries will be essential to establish causal pathways.

CONCLUSIONS

This study conceptualizes European longevity as a multi-dimensional structure driven by a complex interplay of demographic, socioeconomic, environmental, and digital assets. By fitting an optimized multivariate model across 32 European territories, our findings confirm that cross-

national life expectancy variations are profoundly shaped by structural elements. Specifically, the expansion of oldest-old demographic cohorts, evidenced by the super-aging index, functions as the most powerful positive predictor of population lifespans. Concurrently, structural gender survival gaps and ambient SO_2 pollution represent the most severe independent constraints on national longevity. Furthermore, this research offers novel macroeconomic evidence directly linking country-level digital literacy to extended population lifespans, bridging individual digital behaviors and macro-level health outcomes.

Territorially, the macro-regional positioning of Andorra at the absolute forefront of European longevity, sustaining a 5-year stationary mean of 83.68 years and a continent-leading 86.20 years for Andorran women, underscores unique sociodemographic characteristics. Microstates can leverage scale-related structural advantages, including comprehensive digital health deployment, minimal industrial footprints, and near-universal active labor participation, to establish potent public health buffers. Hierarchical Cluster Analysis reinforces this spatial framework, isolating Andorra, Malta, and Luxembourg within a cohesive small-country cluster that exemplifies how compact nations can offer vital paradigm models for optimized public health infrastructure. However, these protective macro-environmental shields operate alongside complex structural indicators, where elevated income inequality and a compressed demographic dependency base must be cautiously interpreted within the country's specific demographic and labor structure.

Future public health research utilizing longitudinal panel data, individual-level registries, and standardized healthy aging markers, specifically tracking nutrition, physical activity, and functional healthspan, will be essential to unravel the precise biological and behavioral pathways involved. Ultimately, while European microstates provide valuable insights for modern health systems, evaluating social equity and long-term demographic balance will be crucial to understanding how Andorra can sustain its leading longevity advantages.

LIST OF ABBREVIATIONS

AROPE – At Risk Of Poverty or Social Exclusion

CO_2 – Carbon Dioxide

EEA – European Environment Agency

EFTA – European Free Trade Association

EU / EU27 – European Union / European Union 27

GDP – Gross Domestic Product

HCA – Hierarchical Cluster Analysis

HIF – Hypoxia-Inducible Factor

LASSO – Least Absolute Shrinkage and Selection Operator

NO – Nitric Oxide

OLS – Ordinary Least Squares

PM10 – Particulate Matter 10 μm

PM2.5 – Particulate Matter 2.5 μm

Q-Q – Quantile-Quantile Plot

SO_2 – Sulfur Dioxide

UV – Ultraviolet

VIF – Variance Inflation Factor

WHO – World Health Organization

DECLARATIONS

Ethics approval and consent to participate

Not applicable. This study does not present any ethical or legal conflicts.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Competing interest

MM is a co-founder of ALMA Life Sciences. The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Authors' contributions

AAO contributed to the study design, data collection, data analysis, interpretation of results, and drafted the manuscript. ADJ contributed to the study design, interpretation of results, and critical revision of the manuscript. MM contributed to the critical revision of the manuscript. All authors read and approved the final manuscript.

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TABLES AND FIGURES

Table 1. Definitions and data sources of analyzed indicators (2020–2024). For the EU27 and EFTA countries, metrics were retrieved from the Eurostat database and the European Environment Agency (EEA). For Andorra, raw microdata and structural indicators were compiled from the Department of Statistics and the Ministry of Environment, Agriculture and Livestock of the Government of Andorra.

Dimension	Variable Name	Definition / Calculation Method	Eurostat Code / Source
Demographics and gender	Life expectancy	Number of years a newborn is expected to live (years).	[demo_mlexpec]
	Life expectancy gap (female - male)	**Authors' calculation**: Difference between female and male life expectancy (years).	[demo_mlexpec]
	Femininity index	Number of women per 100 men in the total population (people).	[eq_pop02]
Dependency and aging	Global dependency ratio	Population 0-14 and >65 relative to those aged 15-64 (%).	[demo_pjanind] (DEPRATIO1)
	Old-age dependency ratio	Population aged >65 relative to those aged 15-64 (%).	[demo_pjanind] (OLDDEP1)
	Young-age dependency ratio	Population aged 0-14 relative to those aged 15-64 (%).	[demo_pjanind] (YOUNGDEP1)
	Aging index	**Authors' calculation**: Population aged >65 relative to those aged <15 (%).	[demo_pjanind]
	Super-aging index	**Authors' calculation**: Population aged >85 relative to those aged >65 (%).	[demo_pjanind]
Poverty and inequality	At-risk-of-poverty (60%)	Population below 60% of median equivalised income (%).	[ilc_li02] (LI_R_MD60)
	Relative poverty (50%)	Population below 50% of median equivalised income (%).	[ilc_li02] (LI_R_MD50)
	Severe poverty (40%)	Population below 40% of median equivalised income (%).	[ilc_li02] (LI_R_MD40)
	Gini coefficient	Measure of income inequity (0 = equality, 100 = inequity).	[ilc_di12]
	S80/S20 income ratio	Ratio of total income received by the top 20% to the bottom 20%.	[ilc_di11]
	Low work intensity	People 0-64 living in households with very low work intensity (%).	[ilc_lvhl11n]
	Severe material and social deprivation	Population unable to afford specific items/activities (%).	[ilc_mdsd11]
	AROPE Index	People at risk of poverty or social exclusion (%).	[ilc_peps01n]
Education and economic prosperity	Education levels 3 and 4	Population with upper secondary and post-secondary education (%).	[edat_lfs_9901]
	Tertiary education (levels 5-8)	Population with tertiary education attainment (%).	[edat_lfs_9901]
	Higher education (30-34)	Tertiary education attainment among the 30-34 age group (%).	[yth_educ_020]
	GDP per capita	Annual gross domestic product at market prices per inhabitant (eur / capita)	[nama_10_pc] (CP_EUR_HAB) (B1GQ)
Emissions and air quality	Greenhouse gas emissions	Net domestic emissions in tons per capita (tonnes / capita).	[sdg_13_10]

	Particulate matter $PM_{2.5}$	**Authors' calculation:** Annual mean concentration in urban areas (µg/m³).	EEA data
	Particulate matter PM_{10}	**Authors' calculation**: Annual mean concentration in urban areas (µg/m³).	EEA data
	Nitrogen dioxide (NO_2)	**Authors' calculation**: Annual mean concentration in urban areas (µg/m³).	EEA data
	Sulfur dioxide (SO_2)	**Authors' calculation**: Annual mean concentration in urban areas (µg/m³).	EEA data
Digital literacy	Internet use	Individuals who used the internet in the last 3 months (%).	[isoc_ci_ifp_iu] (I_IU3)
	e-Government	Individuals using the internet for administrative activities (%).	[isoc_ciegi_ac] (I_IUGOV1)
	e-Health/telemedicine	Individuals seeking health information or accessing medical files (%).	[isoc_ciegi_ac] (I_IGOVIP)
	Digital intensity	Digital intensity by size class of enterprise (%).	[isoc_e_dii]
Quality of life	Overall life satisfaction	Self-reported overall satisfaction with life (scale 0-10).	[ilc_pw01]
	Happiness (last 4 weeks)	**Authors' calculation**: People reporting being happy "always" or "most of the time" (%).	[ilc_pw08]

Figure 1. Evolution of life expectancy (2020-2024). Longitudinal trajectories of global life expectancy at birth in Andorra compared against European Union (EU) and European Free Trade Association (EFTA) ranges (2020–2024). Shaded areas illustrate the range between the highest and lowest mean values for the EFTA and the EU: Switzerland and Iceland (EFTA Highest/Lowest), and Spain and Bulgaria (EU Highest/Lowest).

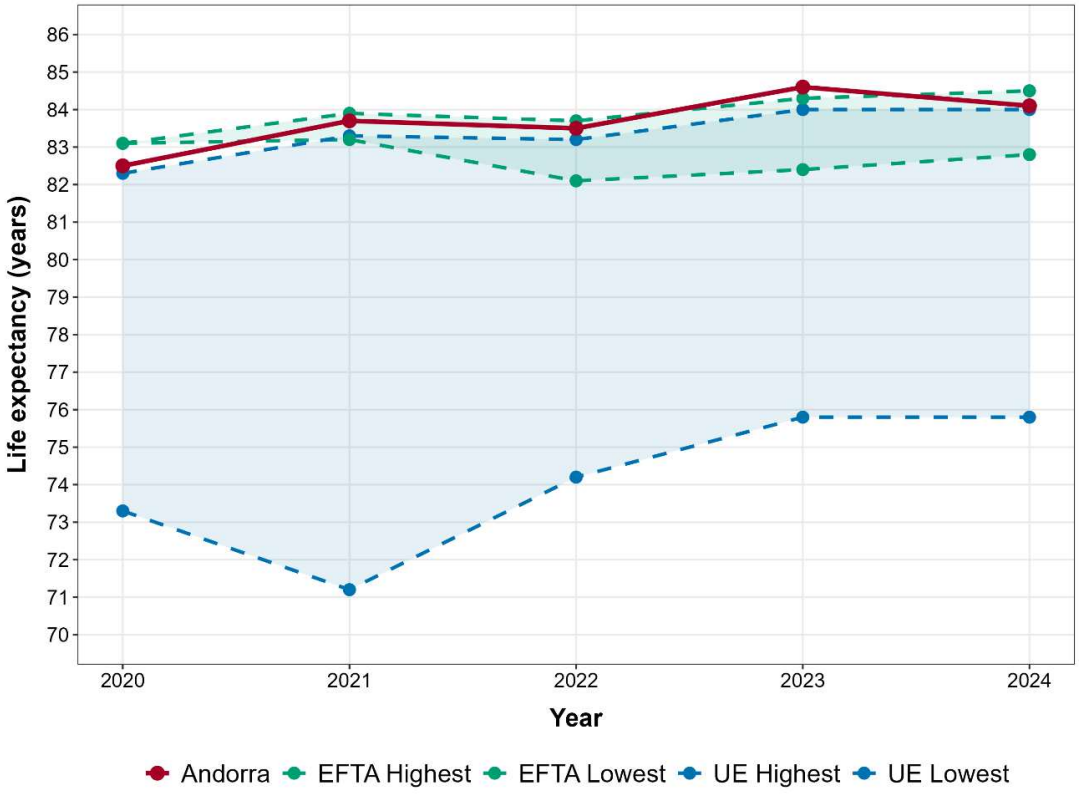


Figure 2. Relationship between life expectancy for men and women across the analyzed countries. 5-year mean (2020-2024) life expectancy is represented; each data point is color-coded according to the life expectancy gap (female - male). The dashed diagonal line represents the 1:1 identity line; all points located above this line indicate a higher life expectancy for women. Horizontal and vertical error bars represent the Standard Error of the Mean (SEM) for men and women, respectively.

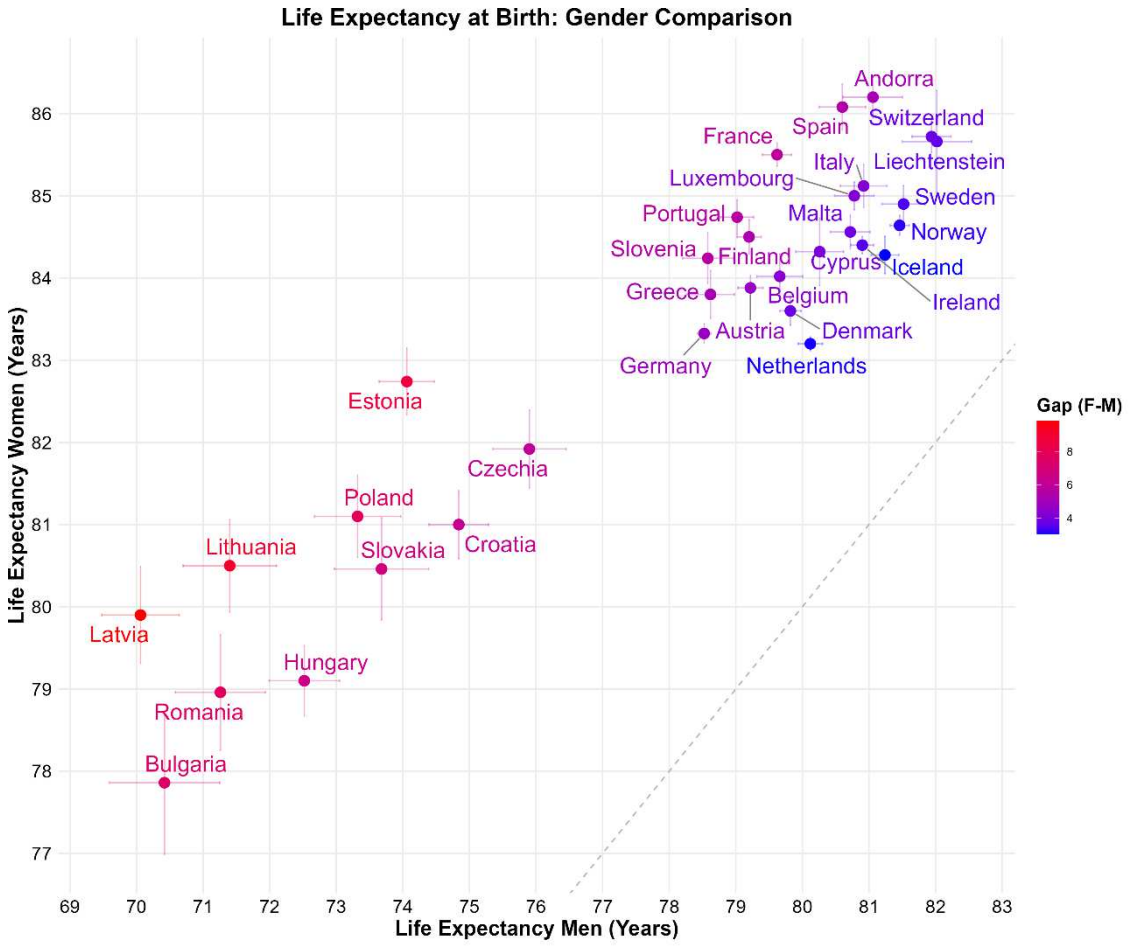


Table 2 Pearson correlation coefficients (*r*) between life expectancy and socioeconomic, environmental and digital indicators across 32 European countries (2020–2024 5-year means). *r* values range from -1.0 (perfect negative linear association) to +1.0 (perfect positive linear association). Statistical significance levels are denoted as follows: * p <0.05, ** p <0.01, *** p< 0.001.

5-year mean variable	Pearson correlation coefficients (*r*)	P-value
Positive correlation vs. life expectancy		
Digital intensity	0.71	0.00001 (***)
Happiness (last 4 weeks)	0.69	0.00002 (***)
Internet use	0.62	0.00018 (***)
GDP per capita	0.59	0.0003 (***)
e-Government	0.49	0.00606 (**)
Overall life satisfaction	0.46	0.00899 (**)
Super-aging index	0.44	0.00977 (**)
Tertiary education (levels 5-8)	0.44	0.01091 (*)
Higher education (30-34 years)	0.44	0.01076 (*)
e-Health/telemedicine	0.37	0.04131 (*)
Low work intensity	0.18	0.3137

Greenhouse gas emissions	0.13	0.46338
Nitrogen dioxide (NO_2)	0.09	0.61981
Negative Correlation vs. life expectancy		
Life expectancy gap (female-male)	-0.84	< .00001 (***)
Education levels 3 and 4	-0.76	0.00001 (***)
Sulphur dioxide (SO_2)	-0.71	< .00001 (***)
Femininity index	-0.67	0.00002 (***)
Severe material and social deprivation	-0.53	0.00162 (**)
Relative poverty (50%)	-0.5	0.00364 (**)
Severe poverty (40%)	-0.48	0.00563 (**)
Particulate matter $PM_{2.5}$	-0.48	0.00525 (**)
AROPE	-0.44	0.0128 (*)
At-risk-of-poverty (60%)	-0.42	0.01594 (*)
Income inequality S80/S20	-0.36	0.04353 (*)
Old-age dependency ratio	-0.29	0.1014
Global dependency ratio	-0.28	0.11351
Particulate matter PM_{10}	-0.27	0.14046
Inequality (Gini coefficient)	-0.22	0.22963
Aging index	-0.16	0.36863
Young-age dependency ratio	-0.05	0.78806

Table 3. Variable selection and coefficient shrinkage via LASSO Regression. Results of the LASSO regularization analysis applied to the set of candidate predictors for global life expectancy. The model was optimized using k-fold cross-validation to determine the penalty parameter (λ_{min}) that minimizes the mean squared error. Variables with non-zero coefficients represent the most robust predictors, as the LASSO algorithm effectively performs automated feature selection by shrinking the coefficients of redundant or non-influential variables to zero. This procedure ensures a parsimonious model, reducing the risk of overfitting and addressing potential multicollinearity among predictors. Predictors are ranked by their estimated standardized effect on life expectancy.

Variable	LASSO Coefficient β
(Intercept)	93.680347679
Life expectancy gap (female - male)	-0.617476678
Super-aging index	0.465427759
Sulphur dioxide (SO_2)	-0.168615005
Femininity index	-0.104610704
Severe poverty (40%)	-0.082796908
Severe material and social deprivation	-0.061432009
Education levels 3 and 4	-0.059052549
AROPE index	-0.016933523
e-Health/telemedicine	-0.008968324

Table 4. Multicollinearity diagnostics (VIF) for the LASSO-selected predictors. Variance Inflation Factor (VIF) values calculated for the subset of variables retained after the LASSO regularization process. The VIF identifies the degree to which the variance of a regression coefficient is inflated due to collinearity with other predictors in the model. VIF values below 5 indicate low and acceptable levels of multicollinearity, ensuring that each predictor provides unique information. Values between 5 and 10 suggest moderate correlation, while values above 10 indicate high multicollinearity that may require further model refinement.

Variable	VIF	VIF after eliminating AROPE
AROPE index	11,637768	/
Severe material and social deprivation	6,178947	3,370006
Severe poverty (40%)	4,962548	2,544274
Sulphur dioxide (SO_2)	3,983919	3,968527
Life expectancy gap (female - male)	3,533492	3,522671

Education levels 3 and 4	3,508105	2,733327
Femininity index	3,383889	3,141888
e-Health/telemedicine	2,183837	2,145366
Super-aging index	1,846492	1,816691

Table 5. Multiple linear regression analysis of 5-year mean socioeconomic, environmental and digital variables vs. life expectancy. Variables selected post LASSO and VIF. Predictors are sorted by statistical significance (p-value). Adjusted $R^2 = 0.959$ ($F(8, 19) = 79.38$, $p < .001$). Statistical significance levels are denoted as follows: * p <0.05, ** p <0.01, *** p< 0.001.

5-year mean variable	Estimate (B)	Std. Error	t value	p-value
Constant	94.89	3.4	27.88	<.001 (***)
Super-aging index	0.49	0.07	6.82	<.001 (***)
Life expectancy gap (female - male)	-0.59	0.12	-4.9	<.001 (***)
Education levels 3 and 4	-0.07	0.02	-3.71	0.001 (**)
Femininity index	-0.11	0.04	-2.81	0.011(*)
e-Health/telemedicine	-0.02	0.01	-2.42	0.026 (*)
Sulfur dioxide (SO_2)	-0.21	0.1	-2.19	0.041 (*)
Severe material and social deprivation	-0.08	0.04	-1.76	0.094
Severe poverty (40%)	-0.14	0.08	-1.69	0.107

Figure 3. Standardized socioeconomic, environmental and digital predictors across European nations. Comparative heatmap displaying standardized Z-scores for the selected structural predictors of life expectancy across European countries. Territories are arranged horizontally along the x-axis in descending order of global life expectancy. Continuous metric features were normalized using column-wise Z-score standardization.

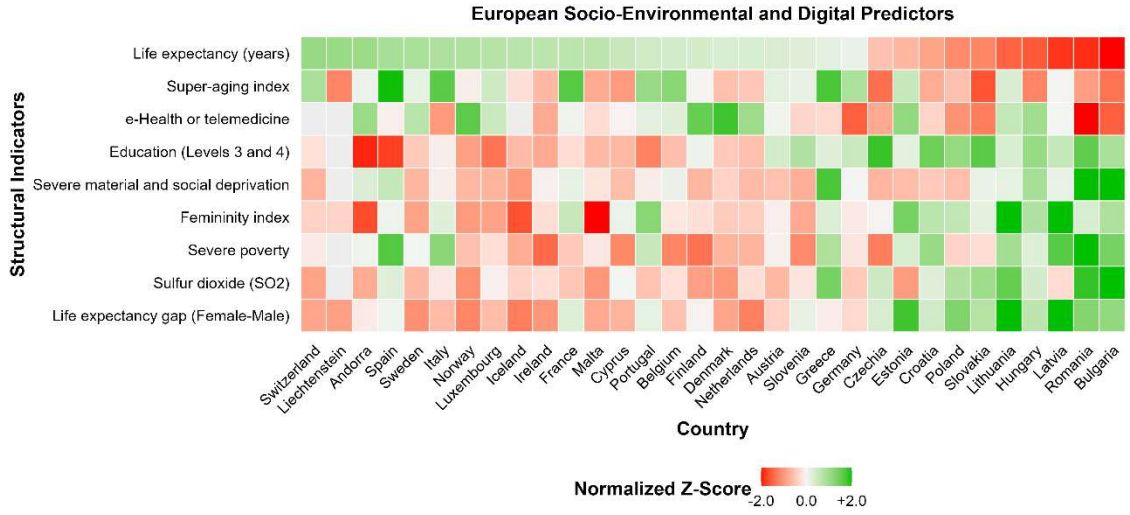
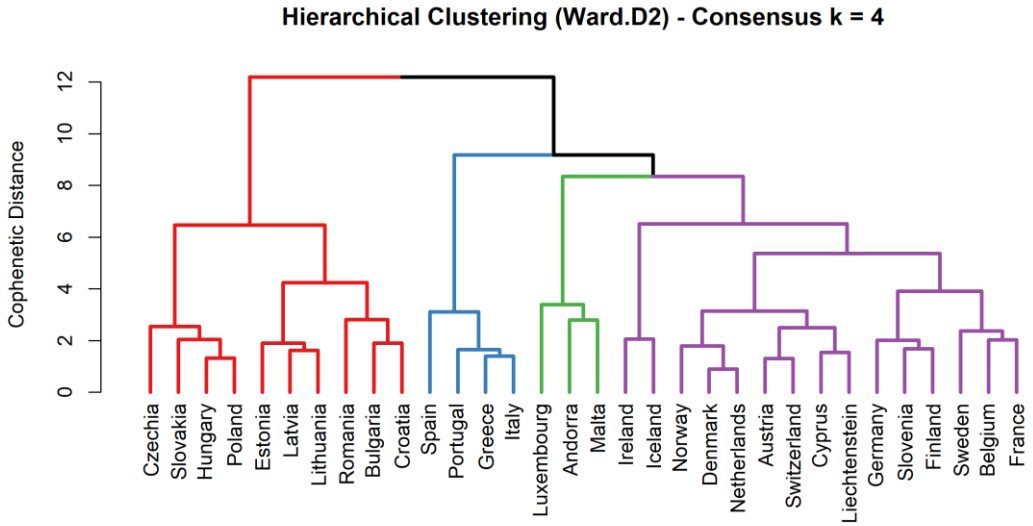


Figure 4. Hierarchical cluster analysis (HCA) dendrogram depicting the multi-dimensional proximity among all 32 European countries analyzed. The clustering algorithm was computed using the Ward's minimum variance method (Ward.D2) applied to a Euclidean distance matrix. To avoid structural distortions and ensure equal weighting, all predictors were standardized via Z-score transformation prior to distance calculation. The input feature space consists exclusively of the optimized subset of predictors that survived the LASSO shrinkage and VIF diagnostics. The optimal division identifies four major clusters (k=4). The y-axis indicates the cophenetic distance (dissimilarity) at which the clusters are merged.

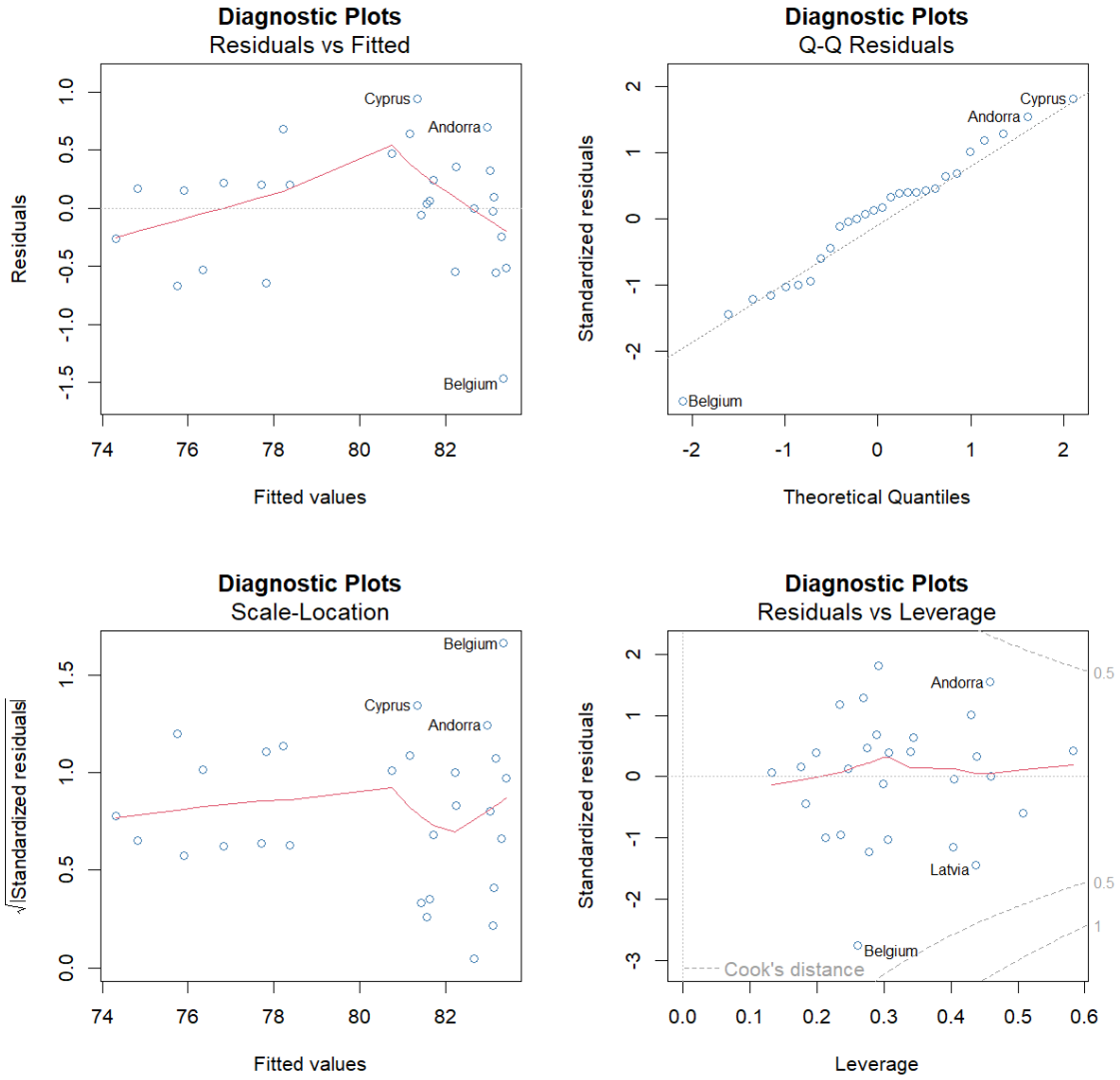


SUPPLEMENTARY TABLES AND FIGURES

Supplementary Table 1. Andorra's 5-year mean and annual trends derived from 5-year longitudinal data of sociodemographic variables across D10 and D1 distributions. Indicators are categorized based on their position within the extreme distribution deciles: the highest tenth percentile (D10, reflecting upper-tail values) and the lowest tenth percentile (D1, reflecting lower-tail values). The analysis provides the 5-year mean baseline, establishing a stationary structural profile, and the annual trend, capturing longitudinal dynamics derived from the latest 5 years. "Top" and "Bottom" rankings represent the highest and lowest absolute metric magnitudes within the sample space, respectively.

	Rank	**5-year mean**
Variable 5-year mean D10		
Gini coefficient	Top 2	36.30
Life expectancy (years)	Top 3	83.68
Variable 5-year mean D1		
Global dependency ratio (%)	Bottom 1	37.41
Youth dependency ratio (%)	Bottom 1	16.87
Education levels 3-4 (%)	Bottom 1	24.08
Low work intensity (%)	Bottom 1	1.66
Old-age dependency ratio (%)	Bottom 1	20.54
Greenhouse gas emissions (Tons per capita)	Bottom 2	2.77
Femininity index	Bottom 2	94.57
	Rank	**Annual trend**
Variable annual trend D10		
Ageing index (%)	Top 1	7.05
Tertiary education levels 5-8 (%)	Top 1	3.17
Gini coefficient	Top 1	1.61
Income inequality S80/S20	Top 1	0.72
At-risk-of-poverty (60%) (%)	Top 2	0.57
Nitrogen dioxide NO_2 ($\mu g/m^3$)	Top 3	0.70
Variable annual trend D1		
Particulate matter $PM_{2.5}$ ($\mu g/m^3$)	Bottom 1	-0.91
Global dependency ratio (%)	Bottom 1	-0.51
Youth dependency ratio (%)	Bottom 1	-0.76
Education levels 3 and 4 (%)	Bottom 1	-1.09
Life expectancy gap (female - male) (years)	Bottom 3	-0.19

Supplementary Figure 1. Residual diagnostics for the multiple linear regression model mapping 5-year mean sociodemographic and environmental indicators against global life expectancy. The diagnostic panel comprises four distinct plots to verify Gauss-Markov assumptions: (A) Residuals vs Fitted values assesses the linearity of the relationships and homoscedasticity, showing a balanced dispersion around the zero-residual baseline; (B) Normal Q-Q plot evaluates the normality of the error distribution, demonstrating that the standardized residuals tightly follow the theoretical normal line, with minor deviations at the extreme quantiles; (C) Scale-Location plot analyzes the homoscedasticity of residuals using the square root of standardized residuals, verifying a stable variance across the predicted fitted range; and (D) Residuals vs Leverage plot detects highly influential data points using Cook's distance thresholds (0.5 and 1.0). Specific case labeling highlights minor residual outliers; however, their positioning safely within the Cook's distance boundaries confirms they do not exert critical leverage or distort the structural stability of the final regression estimates (R^2 = 0.96, Adjusted R^2 = 0.959).



Supplementary Table 2. Socioenvironmental profiles of the top 5 European countries in life expectancy. The table presents the mean indicator values alongside their respective national placement ("Mean Rank", where #1 represents the highest value within the European sample). The "Annual Trend" column quantifies the average annual rate of change over the analyzed time series, with its corresponding European ranking. Missing data values (NA) indicate parameters for which stationary or longitudinal data was insufficient.

	Switzerland		Liechtenstein		Andorra		Spain		Sweden	
	Mean	**Trend**	**Mean**	**Trend**	**Mean**	**Trend**	**Mean**	**Trend**	**Mean**	**Trend**
Life expectancy (years)	83.9 (#1/32)	0.32 (#18/32)	83.78 (#2/32)	0.5 (#8/32)	83.68 (#3/32)	0.41 (#14/32)	83.36 (#4/32)	0.41 (#13/32)	83.22 (#5/32)	0.37 (#16/32)
Super-aging index (%)	14.21 (#7/32)	-0.14 (#22/32)	9.7 (#29/32)	0 (#15/32)	12.53 (#15/32)	-0.21 (#27/32)	16.66 (#1/32)	-0.18 (#24/32)	12.74 (#13/32)	0.11 (#8/32)
e-Health or telemedicine (%)	NA	NA	NA	NA	72.58 (#5/29)	NA	48.3 (#17/29)	NA	65.34 (#8/29)	NA
Education levels 3 and 4 (%)	42.18 (#17/31)	-0.95 (#26/31)	NA	NA	24.08 (#31/31)	-1.09 (#28/28)	25.4 (#30/31)	0 (#10/28)	39.27 (#19/31)	-0.71 (#22/28)
Severe material and social deprivation (%)	2.08 (#29/31)	0.22 (#10/30)	NA	NA	7.06 (#6/31)	-0.31 (#23/30)	8.36 (#5/31)	0.03 (#14/30)	2.24 (#26/31)	0.31 (#5/30)
Femininity index	101.42 (#23/32)	-0.08 (#17/32)	101.56 (#22/32)	-0.03 (#12/32)	94.57 (#31/32)	-0.8 (#30/32)	103.96 (#15/32)	0.05 (#8/32)	98.68 (#28/32)	-0.05 (#14/32)
Severe poverty (40%) (%)	4.98 (#15/31)	0.12 (#11/30)	NA	NA	5.42 (#12/31)	0.06 (#13/30)	9.06 (#2/31)	-0.41 (#26/30)	5.28 (#13/31)	0.19 (#9/30)
Sulfur dioxide (SO_2) ($\mu g/m^3$)	0.91 (#26/31)	-0.21 (#29/31)	NA	NA	1.12 (#25/31)	-0.07 (#16/31)	3.62 (#10/31)	-0.07 (#15/31)	1.49 (#23/31)	-0.49 (#31/31)
Life expectancy gap (female - male) (years)	3.78 (#25/32)	-0.16 (#29/32)	3.64 (#27/32)	0.2 (#1/32)	5.14 (#17/32)	-0.19 (#30/32)	5.48 (#14/32)	-0.15 (#26/32)	3.38 (#29/32)	-0.15 (#27/32)