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Health status in the era of digital transformation and sustainable economic development

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Abstract

Background In the contemporary landscape characterized by digital transformation and sustainable economic development, understanding the dynamics of health status is critically significant. This study investigates the complex relationship among healthcare expenditure, digital transformation, health status, and well-being within the European Union (EU) framework.

Methods Through structural equation modeling, the research examines the multidimensional interplay among these variables, while cluster analysis supports identifying distinct patterns within the data. The paper aims to provide a broad understanding of the impact of digital transformation and healthcare expenditure on health status and well-being at the EU level.

Results The findings unveil nuanced linkages among healthcare expenditure, digital transformation, health status, and well-being across distinct clusters of EU countries. While certain countries exhibit synergistic advancements resulting in enhanced healthcare outcomes, others confront challenges stemming from disparities in digital infrastructure, healthcare expenditure allocation, and health status.

Conclusions This study underscores the imperative of fostering synergies between digital transformation and healthcare expenditure to enhance health status within the EU. Identifying pivotal determinants and barriers enables policymakers to formulate targeted strategies to mitigate disparities and foster inclusive growth to promote equitable healthcare access and advance overall societal well-being.

Keywords Digital transformation, Sustainable economic development, Health status, Healthcare expenditure, European union

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Introduction

The digital transformation in healthcare has increasingly become a significant topic for researchers and industry professionals as technology reshapes how medical services are delivered and managed [1]. This rise in research underscores the need to understand better how technology can address current challenges and issues within the healthcare system and to identify the most efficient and effective methods for implementing digital solutions in medical practice [2, 3].

Digital technologies have revolutionized how healthcare professionals interact with each other and patients [3, 4], facilitating collaboration among various departments within medical institutions and enabling the rapid and secure exchange of medical information. This digital transformation represents a turning point in modernizing the healthcare system and improving the quality of medical care [5]. Furthermore, digitalization in healthcare enhances the efficiency and quality of medical services, contributes to innovation, and fosters sustainable economic development in this vital sector, ultimately improving well-being [6].

Understanding the interconnectedness of sustainability and digital transformation offers a comprehensive perspective on how organizations can integrate these dimensions to promote more sustainable and responsible development [7]. Using digital technologies to monitor and evaluate environmental impact or to enhance operational efficiency can be a central aspect of a sustainable strategy [8, 9]. At the same time, adopting a sustainable approach encourages organizations to develop digital solutions that promote sustainable social and environmental values [3]. The European Union (EU) now grapples with discrepancies in digital infrastructure capabilities, economic inequalities between countries and regions, and uneven access to healthcare services among its member states. Current theoretical research has not fully addressed these challenges, particularly in understanding how digital transformation and healthcare expenditures influence health status and well-being.

This paper investigates the complex relationship between digital transformation, healthcare expenditures, and health status within the EU. The research employs structural equation modeling to examine the multidimensional interactions between these variables and uses cluster analysis to identify distinct patterns within the data set. The study's main objective is to provide a broad understanding of how digital transformation and healthcare expenditures impact health status and well-being at the EU level.

This paper brings novelty and originality by investigating the complex relationship between digital transformation, healthcare expenditures, and health status within the EU, a relationship that has not been fully explored in previous research. Through structural equation modeling, the empirical study provides a data-driven and holistic approach to unravel the multidimensional interactions between these variables. Furthermore, cluster analysis is employed to identify distinct patterns and groupings among EU member countries, revealing potential disparities and variations in healthcare outcomes. The paper examines the impact of digital transformation and healthcare expenditures on health status and well-being at the EU level, providing valuable insights for policymakers and stakeholders. Another original contribution is exploring the synergistic progress of some EU member states in leveraging digital transformation and healthcare investments while also highlighting the challenges others face due to disparities in infrastructure, economic growth, and accessibility to healthcare services. Ultimately, the paper offers a broad understanding of the interaction between healthcare expenditure, digital transformation, health status, and well-being, taking part in developing more effective and sustainable healthcare strategies within the EU.

Digitalization in the healthcare sector can yield significant benefits, such as improving access to healthcare services, improving diagnostic and treatment efficiency, and reducing costs. However, concerns also exist regarding the confidentiality of medical data, information security, and disparities in technology access among different communities [10]. Therefore, a careful analysis of the influences of a country's level of digital transformation and budgetary expenditures on health status and well-being is essential to maximize benefits for all users while ensuring protection and equity.

Literature review and hypotheses development

Digital transformation in healthcare

Digital transformation is essential for organizations to remain competitive and relevant. It drives efficiency, innovation, customer satisfaction, scalability, security, and sustainability, which are critical in today's dynamic economic and social landscape. Adopting digital technologies enhances current processes and paves the way for novel opportunities in innovation and growth [11]. Focusing on organizational culture, employee competencies, and technological infrastructure is decisive in achieving an effective and sustainable digital transformation [12]. Successful change management and a clear digital transformation strategy are fundamental for a smooth transition [13]. Organizations that embrace a proactive and adaptable mindset can fully exploit their potential and secure competitive advantages in the market.

Digital transformation in healthcare impacts the training and education of healthcare professionals [14–18]. Integrating digital technologies into medical education enables students and healthcare professionals to acquire the necessary skills and knowledge more interactively and efficiently [10, 19, 20]. Computer simulations and virtual reality provide practical learning and training opportunities within a safe and controlled environment [20, 21]. Telemedicine and video consultations improve communication with patients, including those in remote or underserved areas. Thus, incorporating digital technologies into medical education fosters a more competent and well-prepared workforce capable of meeting the complex demands of the healthcare sector [22].

Investing in e-health solutions can support disease management, reduce the workload of healthcare staff, and enhance overall care efficiency and quality [23, 24]. Moreover, beyond its benefits in disease management and workload reduction for healthcare staff, investing in e-health solutions also plays a crucial role in optimizing access to Emergency Rooms. As Numico et al. [25] highlighted, e-health technologies can facilitate appropriate patient triage and referrals, ensuring that ERs are used efficiently. This approach improves hospital resource allocation and enhances the timeliness and effectiveness of treatments provided in emergency settings. By reducing unnecessary ER visits and streamlining patient flow, digital health solutions contribute significantly to healthcare services' overall efficiency and quality. Digital health also presents new opportunities for patient engagement. Patients can become more informed and involved in healthcare decisions by accessing relevant medical information and using digital tools like health apps [21]. Integrating digital technologies into healthcare delivery improves the quality of medical care and increases patient satisfaction and autonomy in managing their health [26–28].

However, implementing new technologies in healthcare can face significant challenges, including employee resistance, high costs, and inadequate infrastructure [13]. Introducing new technologies necessitates fundamental changes in existing processes and practices, which can be problematic in the complex and rigid environment of the healthcare system [28]. Nonetheless, with proper planning and management, these technologies can bring substantial benefits, such as improved care quality, enhanced operational efficiency, and cost reduction. Future investments and efforts in healthcare digitization are expected to increase, focusing on innovation and adopting technological solutions better to address healthcare needs and challenges [29, 30].

The paper proposes the first research hypothesis concerning digital transformation in the healthcare sector:

Hypothesis H1. The level of digital transformation positively influences health status within EU countries.

The importance of healthcare expenditures for population well-being and economic development

Public health is an essential field for the well-being and prosperity of a society. Ensuring access to quality healthcare services for all citizens, regardless of their social or economic status, is crucial for promoting health and preventing diseases. Health investments can significantly impact workforce productivity, reducing workplace absenteeism and healthcare costs [31]. A healthy population is more productive, has fewer workplace absences, and is less likely to suffer from chronic diseases or be affected by epidemics, contributing to economic stability and long-term economic growth [32, 33]. Governments can promote sustainable community development and well-being by investing in medical infrastructure, health education, and disease prevention programs. Investments in improving access to healthcare services and promoting a healthy lifestyle can have significant economic benefits [34]. Reduced healthcare spending can free up financial resources for other sectors, thus contributing to overall economic development [35].

Healthcare public expenditures improve the quality of medical services and enhance the population's health status [36]. Underfunding medical infrastructure and human resources can lead to inadequate medical services and poorer health outcomes for the population. Adequate long-term investments in medical infrastructure and training personnel are essential to ensure a sustainable healthcare sector. Well-managed public policy to enhance access to healthcare services can significantly improve quality of life and reduce health inequalities [37]. Furthermore, a robust healthcare system can better respond to public health emergencies, such as pandemics or natural disasters, minimizing their impact on the population and the economy.

Investing in preventive care and health education programs can also reduce the burden on healthcare systems by promoting healthy behaviors and early detection of diseases. Preventive measures (vaccination campaigns, cancer screening, and promoting physical activity and healthy diets) can significantly reduce chronic diseases' incidence and associated costs.

From this perspective, the paper proposes the second research hypothesis regarding healthcare expenditures:

Hypothesis H2. The level of healthcare expenditures significantly influences health status within EU countries.

This hypothesis highlights the importance of adequate healthcare funding in improving the overall health of a population by analyzing data from EU countries.

Sustainability of healthcare systems undergoing digital transformation

Facing financial pressures and challenges related to accessibility and quality of healthcare services, healthcare providers must adapt their practices and use digital technologies to offer efficient and sustainable care. These practices may include adopting sustainable business practices to reduce operational costs and minimize environmental impact [38]. Mixing digital transformation and sustainability in healthcare can bring multiple benefits, including increased operational efficiency, improved service quality, and expanded access to medical care [3, 39–42]. Integrating these two aspects can create more resilient, efficient, and sustainable healthcare systems that better respond to patient needs and ensure access to quality services for all [9].

The sustainability of healthcare systems undergoing digital transformation is essential to ensure continuous access to quality healthcare services and streamline the management of medical resources [43]. Digital technologies can contribute to managing chronic diseases and preventing unplanned hospitalizations, facilitating telemedicine and remote monitoring. Paying attention to their long-term sustainability is essential to keep these systems running and continually improving [44]. Adopting digital technologies such as telemedicine, electronic health records, and data analytics can make healthcare systems more agile, precise, and efficient [45]. These systems' environmental impact and financial efficiency must be evaluated to ensure their long-term viability and bring tangible benefits [46].

Digital transformation in the healthcare sector can contribute to achieving multiple SDGs [47]. Implementing digital healthcare systems can improve health status and access to healthcare services, including in marginalized or isolated communities, thus achieving SDG 3 [48, 49] and promoting a just and healthier world for all.

The paper proposes the third research hypothesis concerning the influence of health on sustainability and general well-being:

Hypothesis H3. The level of health status within EU countries positively influences progress towards achieving Sustainable Development Goal 3 (SDG 3).

Figure 1 illustrates the theoretical model proposed to highlight the impact of digital transformation and healthcare expenditure on health status and general well-being.

Efforts by the EU to promote digital health policies have significant benefits for member states. EU can contribute to reducing disparities in access to technology and digital health services, coordinating and facilitating the exchange of best practices and resources among countries [50]. European institutions can accelerate the adoption of digital technologies and increase the effectiveness and quality of healthcare services across the European Union, setting standards and directions for digital technology implementation while providing funding and support for digital transformation projects [51].

Data on healthcare spending in different EU countries highlight significant differences in approaches to healthcare financing and access [31]. These differences can significantly impact the quality of medical care and health status. Governments and international organizations must continue monitoring and addressing these disparities to ensure equitable access to healthcare services and improve health outcomes globally.

The similarities and differences between EU states regarding healthcare expenditure, digital transformation, health status, and well-being have led us to formulate the fourth research hypothesis:

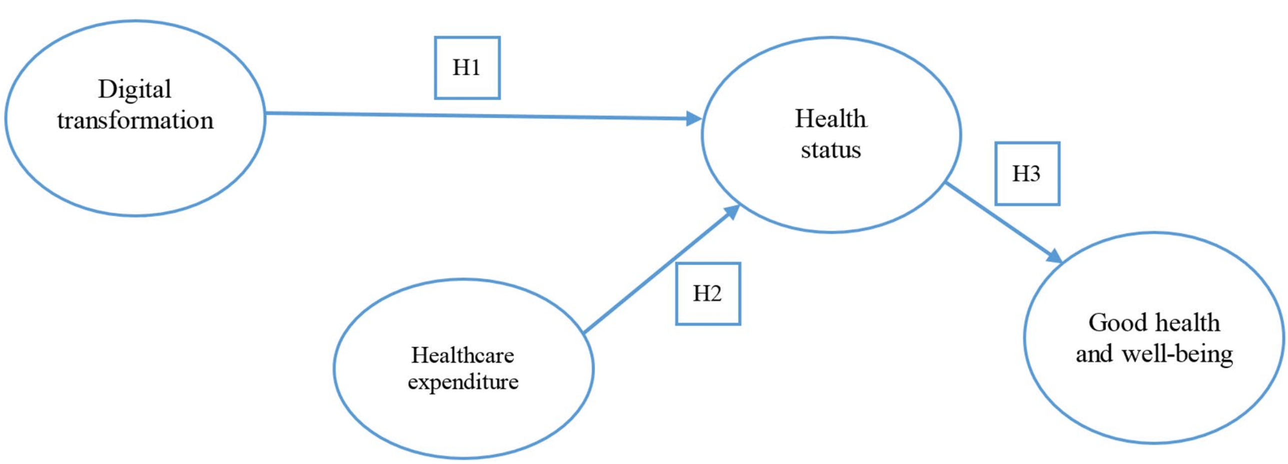

Fig. 1 Theoretical model. Source: authors' design

Hypothesis H4. EU states can be grouped into homogeneous clusters based on their levels of digital transformation, healthcare expenditures, health status, and progress toward achieving SDG 3.

This hypothesis assumes that some common patterns and trends regarding these indicators can be identified among EU states, and ranking them into distinct clusters could help identify specific policy patterns and strategies for promoting digital transformation and health in the EU.

Research methodology

The methodology used in the research involved the use of two statistical techniques, Structural Equation Modeling (SEM) and cluster analysis, for processing and interpreting data collected from Eurostat for healthcare variables [52–56], from the European Commission for digital transformation variables [57], and the Sustainable Development Report for SDG 3 [58]. The collected data includes a panel covering the 27 EU countries from 2017 to 2021. Data characterizing the research variables were available only for this selected period.

Structural Equation Modeling (SEM) is an advanced statistical technique that examines the complex relationships between observable variables and latent variables [59], allowing the use of heterogeneous data sources without the need for data normalization [60, 61]. The SEM model used will be a mixed formative-reflexive model. The model will include both formative variables, measured by their observable variables [59, 62]. This study's latent variables are healthcare expenditure, digital transformation, health status, and well-being.

Digital transformation is a formative variable and has digital technology integration and human capital as observable variables, two components of DESI (Digital Economy and Society Index). The importance of these two components in healthcare is significant. Digital technology integration can lead to better medical data management, improved diagnosis and treatment, increased efficiency, and reduced medical errors. At the same time, well-prepared human capital is essential to ensure adequate use of these technologies.

DESI is a tool the European Commission used to measure the degree of digitalization of the economy and society in EU member states [57]. It provides an overview of digital progress in areas such as internet connectivity, digital skills, use of online services, and integration of digital technology. Integrating digital technology into the healthcare sector can improve the efficiency, accessibility, and quality of medical services. Human capital in healthcare refers to the skills and abilities of healthcare sector personnel in using and implementing digital technology. Well-prepared and adaptable human capital is decisive for ensuring the efficient and beneficial implementation of digital technologies in the healthcare sector.

Healthcare expenditure is a reflexive variable with two observable indicators calculated by Eurostat [52, 53]: current healthcare expenditure and the percentage of gross domestic product for long-term healthcare expenditure. Current healthcare expenditure (CHE) represents the total amount allocated for healthcare services in a specific period, region, or country. These expenditures include funding for hospitals, procurement of medicines, home care services, and similar services. CHE is essential for assessing the financial resources allocated to ensure healthcare services and monitoring their evolution over time. The GDP percentage for long-term healthcare expenditure indicates the share of a country's economic resources allocated to long-term healthcare. This indicator provides insight into the prioritization and allocation of resources for long-term healthcare in the overall context of the national economy.

Health status is a formative variable with three observable variables calculated by Eurostat [54–56]: share of people with good or very good perceived health, healthy life years at birth, and healthy life years at age 65. Sustainability in health is illustrated by the latent variable of good health and well-being with the observable variable SDG 3 score [58]. The SDG 3 score reflects progress regarding access to healthcare services, reducing health inequalities, preventing and treating diseases, promoting mental and physical health, and other aspects relevant to improving health and human well-being.

Table 1 presents the research variables, measurement scales, and data sources.

Cluster analysis is a technique used to identify homogeneous groups of objects or units within a dataset [62]. In this study, cluster analysis identifies distinct patterns and groupings among EU countries based on variables related to digital transformation, healthcare expenditure, health status, and SDG 3. This method groups countries based on similarities, thereby enabling a deeper understanding of differences and similarities among EU member states. Combining SEM with cluster analysis can help identify and evaluate complex interactions between investigated variables, thereby providing a deeper and more comprehensive understanding of the healthcare sector within the EU.

Results

In the research concerning structural equation modeling, we chose to use Smart PLS v3.0 software. This tool provides a powerful and user-friendly platform for data analysis and SEM model building [59]. The model used in our analysis is formative-reflexive. Figure 2 presents the applied model, observable and latent variables, and their relationships.

Table 1 Research variables

Latent variables	Observable variables	Data sets	Measures	Data sources
Digital transformation	HC	Human Capital	Score	[57]
	IDT	Integration of Digital Technology	Score	[57]
Healthcare expenditure	LTCH	Long-term care (health) - Percentage of gross domestic product (GDP)	Percentage	[52]
	CHE	Current health care expenditure (CHE)	Euro per inhabitant	[53]
Health status	GVGPH	Share of people with good or very good perceived health – 16 years or over	Percentage	[54]
	HLYB	Healthy life years at birth	Years	[55]
	HLYA65	Healthy life years at age 65	Years	[56]
Good health and well-being	SDG3	GOAL 3: Good Health and Well-being	Aggregate score (1–100)	[58]

Source: developed by authors based on [52–58]

The validity of a formative model is essential to ensure that latent variables are well-defined and measured by their observable indicators. This testing involves checking the outer weights of these latent variables, which represent the coefficients estimating the relationship between endogen exogen (observable) variables and endogen (latent) variables within the model [60]. In contrast, for a reflexive model, validity involves assessing the outer loadings, which measure the importance of each observable variable in explaining the corresponding latent variable [61]. The outer loadings for latent variables in a reflexive model should exceed the threshold of 0.7 to be significant and adequate [62], indicating that each observable variable significantly contributes to measuring the associated latent variable.

To evaluate the significance of outer weights and outer loadings, we used a bootstrapping procedure with 10,000 samples, with significance $p < 0.05$, thus ensuring the robustness and accuracy of the analysis. The table presents the significance level for each outer weight and outer loading.

The data presented in Table 2 suggest a significant association between observable variables and corresponding latent variables, thus validating the SEM model and providing a solid basis for interpreting its relationships. Checking the reliability of a formative model is important to ensure that variables are well-defined and that there are no multicollinearity issues among them. Multicollinearity can affect the reliability and correct interpretation of the model results [63]. One of the indicators used to assess multicollinearity is the Variable Inflation Factor (VIF). In validating a formative model, all VIFs must register values below 5 [60]. Table 3 presents the multicollinearity indicators.

The Variance Inflation Factor (VIF) values in Table 3 indicate the absence of significant multicollinearity among the variables. Validating an SEM model also involves analyzing the model fit, including SRMR (Standardized Root Mean Square Residual) and NFI (Normed

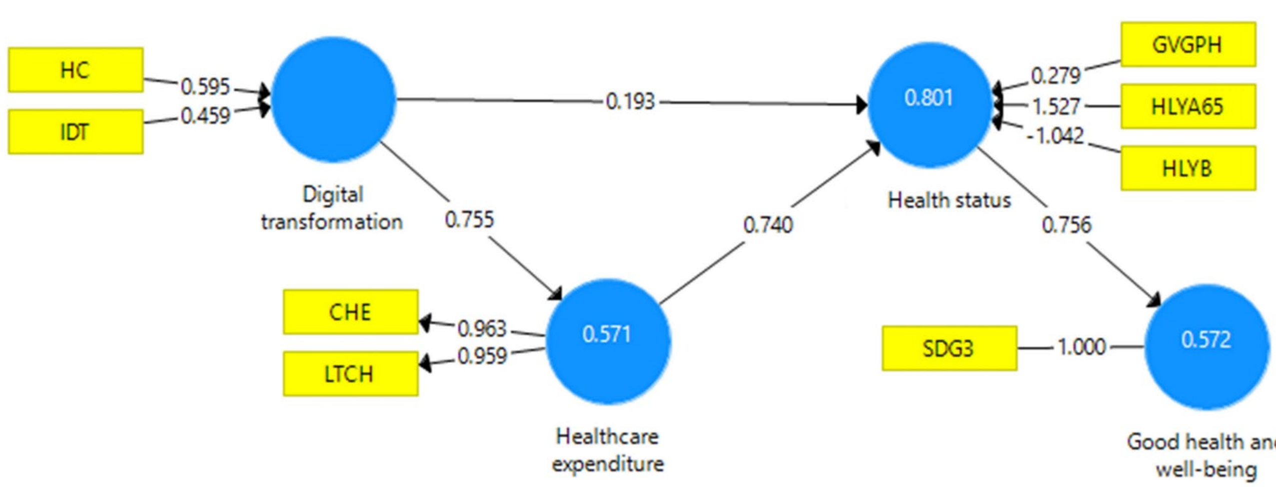

Fig. 2 Applied model. Source: authors' design using SmartPLS v3.0

Table 2 Variables outer weights and loadings

Latent variables	Outer weights and loadings	Original Sample	Sample Mean	Standard Deviation	T Statistics	*P* Values
Digital transformation outer weights	IDT → Digital transformation	0.459	0.458	0.111	4.151	< 0.001
	HC → Digital transformation	0.595	0.594	0.108	5.504	< 0.001
Health status outer weights	GVGPH → Health status	0.279	0.282	0.062	4.487	< 0.001
	HLYA65 → Health status	1.527	1.525	0.094	16.199	< 0.001
	HLYB → Health status	−1.042	−1.046	0.103	10.151	< 0.001
Healthcare expenditure outer loadings	Healthcare expenditure → LTCH	0.959	0.959	0.008	125.593	< 0.001
	Healthcare expenditure → HE	0.963	0.964	0.006	152.479	< 0.001

Source: authors' calculation using SmartPLS v3.0

Table 3 Variable inflation factor

Variable	VIF
IDT	2.747
HC	2.747
GVGPH	1.667
HLYA65	3.188
HLYB	3.479
LTCH	3.567
CHE	3.567
SDG3	1.000

Source: authors' calculation using SmartPLS v3.0

Table 4 Model fit measures

	Saturated Model
SRMR	0.058
d_ULS	0.12
d_G	0.134
Chi-Square	107.892
NFI	0.901

Source: authors' calculation using SmartPLS v3.0

Fit Index). SRMR measures the discrepancy between the observed variance-covariance matrix and the estimated model matrix. The lower the SRMR value, the better the model fits the data. A low SRMR value of 0.08 indicates a good fit of the model to the observed data [60]. NFI is a normed fit index that compares the fit of the proposed model to the fit of a reference model. An NFI value greater than 0.90 is acceptable for the model fit to the observed data [63]. Table 4 presents the model fit measures.

Using a bootstrapping procedure with 10,000 two-tailed samples and $p < 0.05$, we calculate the direct and total effects between the latent variables of the model, as well as determine the significance levels of these influences. Obtaining robust coefficients and significance level estimates involves generating 10,000 samples of similar sizes to the original dataset [60]. Therefore, by applying this bootstrapping procedure, we can obtain reliable and robust estimates of the effects between the latent variables and assess their significance levels rigorously and objectively. Table 5 presents the direct and total effects of the model.

Table 5 discloses a significant direct effect of digital transformation on health status (0.193, $p = 0.004$). Furthermore, the total effect is significant (0.752, $p < 0.001$), validating the H1 Hypothesis. Investigating the H2 Hypothesis, we found a significant direct effect of healthcare expenditure on health status (0.74. $p < 0.001$). Based on this data, the H2 Hypothesis is validated. Investigation of the H3 Hypothesis shows that the direct effect of health status on well-being (0.756, $p < 0.001$) is significant, indicating a direct and positive influence of health status on well-being, quantified by the SDG 3 level of each country. In conclusion, the data confirm the validity

Table 5 Direct and total effects within the model

Effects	Path	Original Sample	Standard Deviation	T Statistics	*P* Values
Direct	Digital transformation → Healthcare expenditure	0.755	0.034	22.469	< 0.001
	Digital transformation → Health status	0.193	0.067	2.875	0.004
	Healthcare expenditure → Health status	0.74	0.059	12.541	< 0.001
	Health status → Good health and well-being	0.756	0.029	26.002	< 0.001
Total	Digital transformation → Good health and well-being	0.569	0.037	15.421	< 0.001
	Digital transformation → Healthcare expenditure	0.755	0.034	22.469	< 0.001
	Digital transformation → Health status	0.752	0.032	23.254	< 0.001
	Healthcare expenditure → Good health and well-being	0.56	0.048	11.571	< 0.001
	Healthcare expenditure → Health status	0.74	0.059	12.541	< 0.001
	Health status → Good health and well-being	0.756	0.029	26.002	< 0.001

Source: authors' calculation using SmartPLS v3.0

of the H3 Hypothesis. Overall, the direct and total effects within the SEM model support the proposed hypotheses and suggest a significant and positive impact of health indicators on well-being within EU countries.

The fourth hypothesis involves using cluster analysis to group EU countries into homogeneous clusters [64] based on the level of digital transformation, healthcare expenditure, health status, and SDG 3. The data used are from 2021, the most recent year for which the selected data was available. We used the Ward method with squared Euclidean distance as the interval distance for cluster analysis. The Ward method is a clustering analysis technique used to group data into homogeneous subgroups, with the advantage of minimizing the internal variation of each cluster. This grouping is achieved by minimizing the sum of squares of differences between points within the same cluster and its center. Using the squared Euclidean distance as the distance metric, the Ward method enables the identification of compact and well-defined clusters, thereby contributing to a more straightforward and precise interpretation of results [65]. This approach helps identify underlying structures and better understand relationships and patterns within the selected dataset. Figure 3 illustrates the dendrogram with three homogeneous clusters.

To analyze indicators related to digital transformation, healthcare expenditure, health status, and SDG 3, we grouped the selected data into three clusters, illustrated by the dendrogram. Table 6 presents the countries grouped into three clusters.

Cluster A comprises countries from Western, Central, and Northern Europe, which stand out for high levels of digital transformation associated with good health status, healthcare expenditure above the EU average, and a high level of SDG 3. Cluster B includes countries from Southern Europe, such as Portugal, Italy, Spain, Cyprus, and Malta, along with two former communist countries, Slovenia and the Czech Republic. The countries in this cluster exhibit moderate digital transformation levels, health status indicators, healthcare expenditure, and SDG 3 levels slightly below the EU average. Cluster C includes former communist countries plus Greece, with lower levels of digital transformation and reduced values of health status indicators and healthcare expenditure. Analyzing these clusters provides an understanding of the diversity of the healthcare situation within the EU, allowing the identification of countries with superior or inferior performance in various analyzed aspects, thus validating hypothesis H4. Figure 4 in Appendix illustrates the graphical appearance of countries in the three clusters.

Discussion

Integrating sustainability and digital transformation into healthcare strategies can bring multiple benefits. Adopting sustainable business practices can help reduce the negative impact on the environment and enhance operational efficiency. Simultaneously, digital technologies can improve access to healthcare services, diagnostic and treatment efficiency, and patient communication and engagement in the healthcare process. Combining innovative business approaches focusing on sustainability and digital transformation can contribute to developing a more efficient, inclusive, and patient-centric healthcare system [38].

This study aimed to analyze and understand the interconnection between digital transformation, healthcare expenditure levels, and health status within the EU. The investigation proposes four hypotheses to provide a clearer perspective on how these variables influence each other and their impact on healthcare systems and population well-being in the European context. This approach provides a deeper and more comprehensive understanding of the complex dynamics in healthcare in the digital era and offers guidance for future policies and practices within the EU.

The results obtained from testing hypothesis H1 are consistent with previous findings in the literature, which have demonstrated the benefits of integrating digital technologies in the healthcare sector [20, 66]. However, the innovation and original contribution of this research lies in the in-depth examination of how these digital technologies can support efforts to improve the quality of medical services in the specific context of the European Union. By implementing advanced information systems and dedicated applications, medical facilities can strengthen their ability to analyze and understand the needs and preferences of patients, allowing them to offer more personalized and efficient services [67]. Technology can also support innovation initiatives within healthcare systems, facilitating the introduction and implementation of new practices and procedures, leading to significant improvements in the quality and accessibility of medical care [68].

The COVID-19 pandemic further underscored the critical role of digital technologies in ensuring the resilience and adaptability of healthcare systems. During this period, the rapid adoption of telemedicine, remote patient monitoring, and AI-driven diagnostic tools became essential in managing healthcare demand, reducing hospital overcrowding, and maintaining continuity of care despite lockdown measures and resource constraints [31]. Countries with more advanced digital

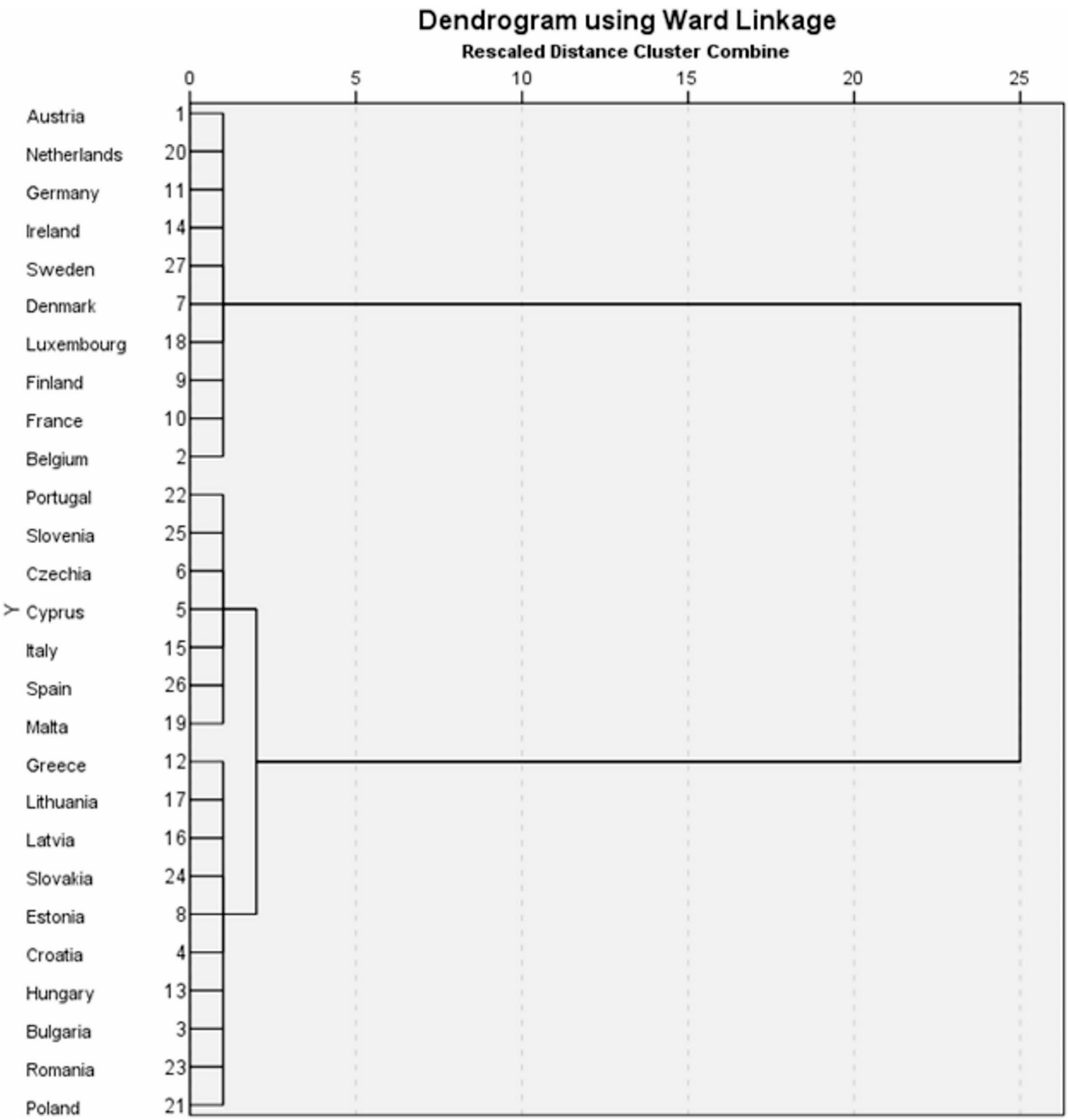

Fig. 3 Dendrogram. Source: authors' design using SPSS v.20

infrastructures were able to respond more effectively to the crisis, optimizing patient triage, facilitating remote consultations, and ensuring real-time data sharing for better decision-making [69]. The pandemic acted as a catalyst for digital transformation, highlighting the benefits and challenges of integrating technology into healthcare on a large scale.

Thus, investments in digital technologies in healthcare can be essential for increasing the healthcare system's effectiveness and efficiency, contributing to improving population health and well-being. However, to provide a comprehensive and innovative perspective, this paper analyzes the impact of these investments in the specific context of EU member countries, considering existing

Table 6 Clusters structure

Clusters	Country	IDT (score)	HC (score)	GVGPH(%)	HLYB (years)	HLYA65 (years)	LTCH(%)	CHE(euro per inhabitant)	SDG3(score)
Cluster A	Austria	8.86	12.70	72.7	61.8	9.5	1.59	5485.57	92.6
	Netherlands	11.72	15.16	73.8	60.3	9.4	3.05	5510.68	95.5
	Germany	7.91	10.84	65.1	65.6	10.8	2.47	5599.48	93.4
	Ireland	11.03	15.11	81.0	67.2	12.6	1.39	5688.64	94.3
	Sweden	12.62	14.97	74.3	68.4	14.6	2.82	5812.60	96.9
	Denmark	13.26	14.39	69.2	56.6	9.9	2.09	6223.01	95.6
	Luxembourg	8.18	13.84	78.4	62.0	11.0	1.04	6402.14	96.8
	Finland	13.35	17.63	72.0	61.7	10.9	1.71	4590.30	95.4
	France	7.47	12.24	70.0	66.2	12	1.95	4542.27	93.4
	Belgium	10.66	11.58	78.8	64.6	11.2	2.34	4789.57	93.4
Mean values of Cluster A		**10.51**	**13.84**	**73.53**	**63.44**	**11.19**	**2.05**	**5464.43**	**94.72**
Cluster B	Portugal	8.43	11.03	54.2	58.3	7.9	0.51	2308.06	92.4
	Slovenia	8.93	10.83	71.5	65.4	10.7	1.03	2351.11	92.5
	Czechia	8.13	11.12	70.3	62	7.6	1.20	2151.86	90.5
	Cyprus	8.05	9.93	77.9	65.7	9.2	0.30	2515.24	91.7
	Italy	9.29	8.88	76.2	68.1	10.7	0.91	2837.00	94.2
	Spain	8.57	12.60	74.0	62.8	10.5	0.95	2733.59	94.6
	Malta	10.88	12.42	75.7	68.7	11.9	1.73	3064.16	91.3
Mean values of Cluster B		**8.90**	**10.97**	**71.40**	**64.43**	**9.79**	**0.95**	**2565.86**	**92.47**
Cluster C	Greece	5.50	10.25	80.1	65.6	7.7	0.15	1576.75	90.7
	Lithuania	8.78	10.21	52.3	57.6	6	0.52	1568.36	85.9
	Latvia	5.61	10.79	54.6	53.8	4.8	0.33	1612.14	84.8
	Slovakia	6.55	10.83	68.4	56.8	5	0.03	1427.52	88.3
	Estonia	8.30	13.26	60.5	56.5	7	0.69	1769.74	89.9
	Croatia	8.59	12.54	64.9	58.6	5.2	0.21	1195.09	87.5
	Hungary	4.59	9.68	68.0	62.5	7.5	0.29	1170.72	84.2
	Bulgaria	3.52	7.88	71.7	63.3	8.4	0.28	884.18	79.3
	Romania	3.92	7.52	77.1	57.8	4	0.33	817.47	80.7
	Poland	5.14	9.08	67.9	62.6	8.3	0.52	983.14	83.9
Mean values of Cluster C		**6.05**	**10.20**	**66.55**	**59.51**	**6.39**	**0.34**	**1300.51**	**85.52**
Mean values at UE level		8.44	11.75	70.39	62.24	9.05	1.13	3170.76	90.73

Source: authors' construction using SPSS

disparities in digital infrastructure, levels of healthcare expenditure, and access to medical services. Including the COVID-19 period in this analysis further strengthens the argument that digitalization is a long-term strategic necessity and a crucial factor in managing healthcare crises and ensuring system resilience.

The findings related to Hypothesis H2 indicate that investments in the public healthcare system significantly influence a population's health status and quality of life. This study extends the understanding by emphasizing the importance of efficient management of these investments [37]. Our research highlights that the magnitude and management efficiency of financial resources is central to maximizing benefits. Effective resource allocation and utilization are essential for enhancing access to quality healthcare services and achieving better health outcomes. This nuanced perspective provides a more detailed insight into how investment strategies can be optimized to improve public health.

The COVID-19 pandemic further reinforced the critical role of healthcare investments, particularly in public health infrastructure, emergency preparedness, and digital transformation [29]. The crisis exposed vulnerabilities in healthcare systems, demonstrating that countries with higher levels of investment and better-managed resources were more resilient in handling the surge in patient demand. The rapid mobilization of financial resources for expanding intensive care capacities, procuring medical supplies, and deploying digital health solutions was instrumental in mitigating the pandemic's impact [69]. Furthermore, the pandemic highlighted the need for sustainable and adaptable healthcare financing strategies, ensuring that health systems can respond effectively to emergencies and long-term public health challenges [31].

The SEM model results confirm the validity of Hypothesis H3, indicating that the level of health status within EU countries positively influences progress towards SDG 3. This research extends the previous research results [49] by highlighting the innovative role of digital transformation in the healthcare sector. Implementing digital healthcare systems improves access to healthcare services and enhances the efficient collection and analysis of health data, thereby supporting progress towards SDG 3.

Our study underscores the importance of maintaining and improving the sustainability of healthcare systems undergoing digital transformation, as shown by other researchers [44, 45]. Ensuring continuous access to quality healthcare services and optimizing the management of medical resources necessitates a focus on long-term sustainability. Key areas requiring attention include funding, infrastructure, education, interoperability, and ongoing innovation. Our research contributes to a deeper understanding of how to construct and sustain efficient digital healthcare systems that support health and well-being goals, addressing these aspects.

To examine Hypothesis H4, we used cluster analysis to group EU countries into three homogeneous clusters, which validated the hypothesis. This approach revealed significant differences in healthcare expenditures and access to services across the EU, offering a comprehensive understanding of healthcare variations within the union.

Our findings extend previous [31, 51] research by providing a nuanced analysis of how countries approach healthcare financing and access. Cluster analysis highlights the specific needs and opportunities of each category of countries, which is crucial for identifying directions for improving healthcare systems at the European level. Notably, countries in cluster A, which exhibit a good health status and healthcare expenditures above the EU average, reflect a strong commitment to providing and accessing healthcare services. In contrast, countries in cluster C are characterized by lower levels of digital transformation and weaker indicators, disturbing the delivery of healthcare services and, more importantly, the health status of their populations. Countries in cluster B are in an intermediate position. These countries are taking significant steps towards digital transformation, investing in modern technologies to improve access and quality of healthcare services. They also allocate significant healthcare expenditures, demonstrating their commitment to improving healthcare systems and ensuring access to adequate medical care for their populations. This study's innovative contribution lies in its detailed clustering methodology, which enables targeted strategies for enhancing healthcare delivery based on each cluster's unique characteristics and requirements.

Digital transformation significantly impacts all aspects of society, including the healthcare sector [70, 71]. Through digital technologies, hospitals and other healthcare institutions can enhance access to healthcare services, improve the efficiency of diagnostics and treatments, manage medical data more effectively, and facilitate communication between professionals and patients [1, 2]. These digital innovations can increase operational efficiency and improve medical care quality [69].

Limitations and further research

Methodological and research limitations include the constraints and limitations of the SEM model, such as the number of variables considered. Data for analysis have temporal limitations, as data for all selected variables were available only from 2017 to 2021. The specific context of the European Union and the particularities of each member country influenced the interpretation of results. Thus, generalizing results may not always be appropriate, and a more detailed analysis at the national or regional level may be necessary.

Regarding future research directions, several aspects could be further explored to complete the understanding of the examined relationship in the EU. Qualitative studies could provide a more detailed perspective on how specific factors, such as digital infrastructure or healthcare policy, influence the implementation and impact of digital technologies in healthcare. In future studies, we will consider incorporating additional observable variables to enhance the robustness of our models, providing a more comprehensive and detailed understanding of the relationships between these critical factors. Observable variables for digital transformation could include the adoption rate of electronic health records, telemedicine usage, and digital literacy among healthcare professionals. For healthcare expenditure, observable variables might comprise government healthcare funding, out-of-pocket expenses, and insurance coverage rates. Health status could be described using variables such as incidence of chronic diseases, mortality rates, and patient satisfaction scores. Good health and well-being could be measured through mental health status and quality of life assessments.

Conclusions

Digital transformation in healthcare goes beyond merely implementing digital technologies; it requires restructuring the entire healthcare system to meet patients' and healthcare professionals' evolving needs and expectations. Integrating digital technologies optimizes existing processes and opens up new opportunities for innovation and improving the quality of medical care. The research findings underline the importance of integrating sustainability and digital transformation into healthcare strategies, highlighting the multiple benefits these two aspects can bring. The research results confirmed the benefits of integrating digital technologies in the healthcare sector, such as improving the quality and accessibility of medical services in the specific context of the European Union. Implementing advanced information systems and dedicated applications in medical facilities can strengthen their ability to analyze and understand the needs of patients, providing them with more personalized and efficient services. Technology can also support innovation initiatives within healthcare systems.

Policy implications

Integrating sustainability and digital transformation into healthcare strategies has significant policy implications. Policymakers should prioritize the development of regulations and incentives that encourage healthcare institutions to adopt digital technologies while ensuring sustainable practices. This approach involves creating funding mechanisms that support investments in digital healthcare infrastructure, promoting interoperability standards to enhance data exchange across systems, and fostering policies that ensure equitable access to digital health services.

Furthermore, addressing disparities in digital infrastructure across EU member countries is essential to achieving a more balanced and efficient healthcare system. Policymakers should develop targeted strategies to support underfunded regions, ensuring all populations benefit from technological advancements. Focusing on long-term sustainability through funding, education, and continuous innovation can contribute to achieving SDG 3 on health and well-being. By integrating digital transformation into healthcare policies, governments can enhance operational efficiency, reduce environmental impact, and improve the overall quality of care.

Managerial implications

From a managerial perspective, adopting digital technologies in healthcare organizations requires a strategic approach to resource allocation, workforce training, and process optimization. Healthcare managers should invest in advanced digital tools that improve patient communication, diagnostics, and treatment efficiency while ensuring that staff members receive adequate training to utilize these technologies effectively.

Moreover, empirical research suggests that efficient resource management is crucial for maximizing the benefits of digital transformation. Healthcare managers should optimize operational workflows to improve service delivery and patient outcomes. Furthermore, collaboration with policymakers and technology providers can help address challenges related to digital infrastructure and ensure seamless integration of innovative healthcare solutions.

Managers should also adopt data-driven decision-making processes, leveraging analytics to monitor performance and identify areas for improvement. By prioritizing digital innovation and sustainable healthcare practices, healthcare organizations can enhance their capacity to deliver high-quality, patient-centric care.

This study confirmed that digital technologies significantly improve healthcare accessibility and quality in the European Union. Adopting advanced information systems and medical applications strengthens healthcare providers' ability to analyze patient needs, delivering more personalized and efficient care. Furthermore, investments in public healthcare systems play a critical role in shaping health outcomes and overall well-being. However, the efficiency of financial resource management is equally important in maximizing these benefits.

The results of the SEM model indicate that a higher level of health status in EU countries positively influences progress towards SDG 3. Furthermore, the innovative role of digital transformation in healthcare has been reaffirmed, demonstrating its impact on medical data collection and analysis. The cluster analysis further highlighted disparities in healthcare expenditures and access across EU nations, emphasizing the need for targeted strategies to bridge these gaps.

Although this study focused on EU countries, expanding the research to a global scale could provide valuable insights into the applicability of these findings in diverse healthcare settings. Future studies should consider global economic, cultural, and regulatory differences in digital healthcare adoption. Conducting comparative analyses between countries will help refine strategies for integrating sustainability and digital transformation in healthcare, ultimately contributing to developing a more resilient and patient-centered global healthcare system.

Appendix

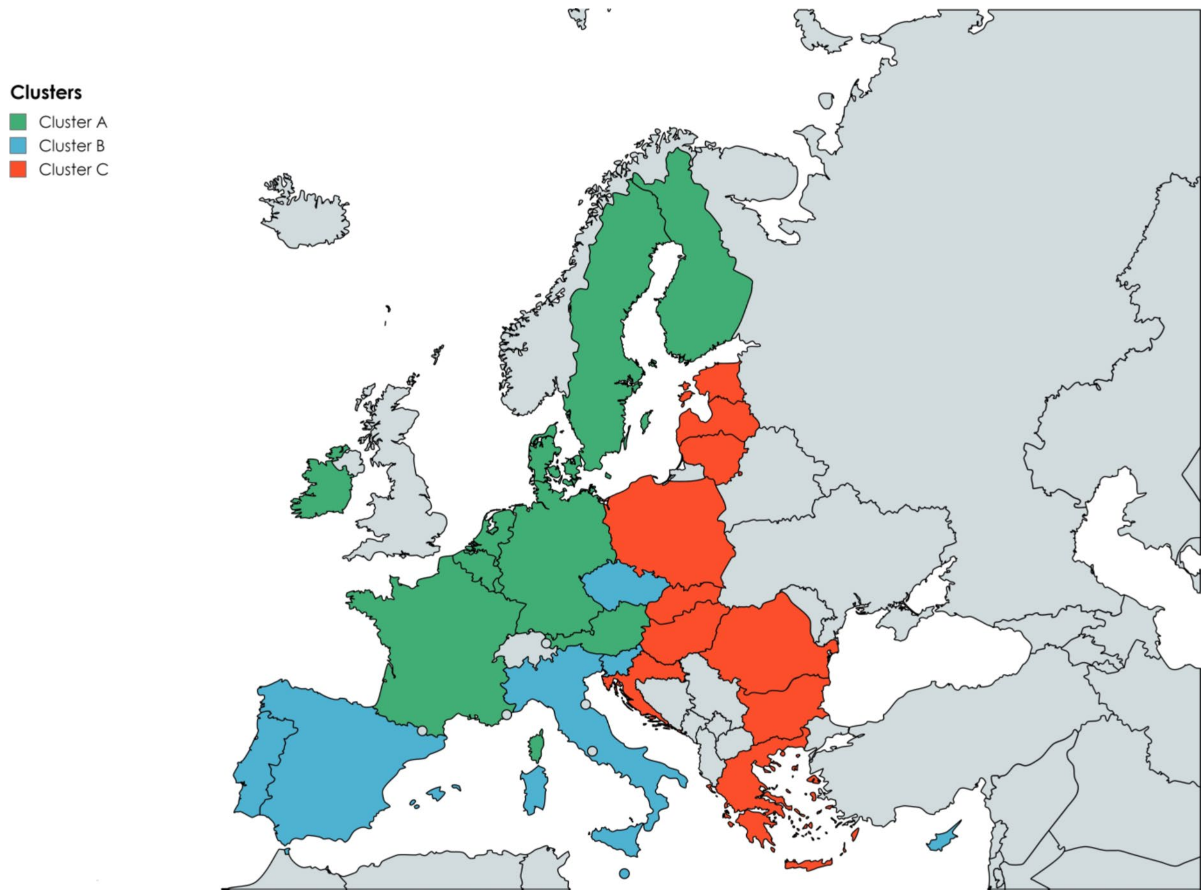

Fig. 4 The distribution of countries across clusters. Source: developed by the author based on collected data from Eurostat using MapChart. Available online: https://www.mapchart.net/ (accessed on 6 April 2024)

Authors' contributions
Conceptualization: AAV and CGB; methodology: AAV and CGB; software: AAV and CGB; validation: AAV and CGB; formal analysis: AAV and CGB; investigation: AAV and CGB; resources: AAV and CGB; data curation: AAV and CGB; writing—original draft preparation: AAV and CGB; writing—review and editing: AAV and CGB; visualization: AAV and CGB; supervision: AAV; project administration: CGB. All authors have read and agreed to the published version of the manuscript.

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Data availability
Data is available in a publicly accessible repository: Eurostat.https://ec.europa.eu/eurostat/databrowser/view/tps00214__custom_10964038/default/table?lang=en. Accessed 29 March 2024.Eurostat.https://ec.europa.eu/eurostat/databrowser/view/tps00207__custom_10964042/default/table?lang=en. Accessed 29 March 2024.Eurostat.https://ec.europa.eu/eurostat/databrowser/view/sdg_03_20__custom_10964049/default/table?lang=en. Accessed 29 March 2024 .Eurostat.https://ec.europa.eu/eurostat/databrowser/view/tps00150__custom_10964053/default/table?lang=en. Accessed 29 March 2024.Eurostat. https://ec.europa.eu/eurostat/databrowser/view/tepsr_sp320__custom_10964051/default/table?lang=en. Accessed 29 March 2024.European Commission. https://digital-strategy.ec.europa.eu/en/policies/desi. Accessed 29 March 2024.Sachs D, Lafortune G, Fuller G. Online database for the Sustainable Development Report. 2024. https://dashboards.sdgindex.org/static/downloads/files/SDR2024-data.xlsx. Accessed 14 November 2024.

Declarations

Ethics approval and consent to participate
Not applicable. This article contains no studies with human participants performed by any authors.

Consent for publication
Not applicable. This article contains no studies with human participants performed by any authors.

Competing interests
The authors declare no competing interests.

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