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Cross-Domain modeling of circular economy and social sustainability transitions in the Visegrád region

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Abstract
Amid rapid structural transitions, the Visegrád region (Czechia, Hungary, Poland, Slovakia) faces urgent challenges in linking circular economy (CE) advances with social sustainability (SS). This study investigates patterns between circular economy practices and social outcomes across Eurostat data (2014–2023) for the region. Results show mixed progress: municipal waste generation is projected to rise moderately, reaching 1500 kg per capita by 2030, while the average circular material use rate is expected to remain modest at 3.6%. In contrast, recycling rates are forecasted to grow substantially, rising from 22% to 37–40% by 2030. However, material import dependency remains stable at approximately 39%. Social indicators demonstrate positive outlooks: regional social protection expenditure is forecasted to reach ~ 18,500 PPS per inhabitant by 2030, while annual net earnings are projected to reach €18,000 by 2030, representing a 260% increase. However, the gender pay gap remains persistent at 13–14% across the region, declining minimally to 13% by 2030. Distinct associations are observed, such as higher circular material use correlating positively with both social protection and health expenditure. Regional comparisons identify Czechia as a consistent leader (indices up to 0.74 for circular economy; 0.68 for social sustainability), while Hungary lags (indices as low as 0.20/0.19). These findings highlight the need to embed equity, gender inclusion, and targeted social investment within circular economy policies. Insights support integrated strategies for tackling persistent waste and healthcare challenges, expanding monitoring, and promoting inclusive green jobs toward a more equitable and sustainable future in the Visegrád region.

Keywords Circular economy, Social sustainability, Cross-domain modelling, ARIMA forecasting, Integrated sustainability assessment

1 Introduction

The transition from linear to circular economic models has become central to sustainability science as concerns about resource depletion, environmental degradation, and social inequality intensify. The circular economy (CE) framework seeks to minimize waste, maximize resource efficiency, and extend product lifecycles, with the European

Union (EU) emerging as a global leader through initiatives like the Circular Economy Action Plan and European Green Deal [1, 2]. However, while CE focuses on resource optimization, social sustainability (SS) emphasizes community well-being and inclusive economic progress, creating potential tensions that require empirical investigation [3].

In addition, the accelerating urgency of planetary boundaries, resource depletion, and social inequality has compelled policymakers and researchers to seek transformative models for sustainable development. Among these, the circular economy (CE) has emerged as a flagship paradigm in European Union (EU) policy, promising to decouple economic growth from environmental degradation by closing material loops and fostering resource efficiency [4, 5]. In this context, the convergence of circular economy practices and social sustainability measures has emerged as a critical focal point for researchers, practitioners, and policymakers alike. Historically, economic paradigms emphasized linear models based on "take-make-dispose" cycles, which inadvertently contributed to resource depletion, waste accumulation, and escalating environmental degradation. However, the growing adoption of circular economy principles over the last few decades reflects a paradigm shift towards key goals. These include revalorizing waste streams, optimizing resource use, and implementing sustainable production models that seek to separate economic growth from environmental degradation [6–8]. Researchers have suggested that embedding circular economy strategies within broader socioeconomic policies not only spurs environmental resilience but also enhances social well-being by creating new job opportunities, improving health outcomes, and reducing inequities. This integrated viewpoint is particularly relevant in regions such as the European Union, where a historical dependence on imported materials, escalating urban waste challenges, and persistent social disparities have prompted both academic and policy-oriented investigations into sustainable development metrics.

Recent academic literature increasingly explores how circular resource flows intersect with social sustainability goals, particularly regarding public health, equity, and quality of life [9, 10]. Empirical evidence suggests that areas with robust recycling systems often exhibit improved public health indices and lower healthcare expenditures, while circular material use rates indicate potential for job creation in sustainability-focused sectors [11, 12]. These findings underscore the importance of employment in circular economy sectors as vital links between environmental policy and social outcomes.

Despite growing interest in CE-SS interactions, three critical research gaps persist. First, while CE's environmental benefits are well-documented, its social consequences remain comparatively under-investigated, particularly regarding employment quality, health access, and gender equity across different regional contexts. Second, existing social sustainability benchmarks often lack clear targets and do not capture interrelationships with broader sustainability goals, necessitating integrated measurement frameworks that systematically align SS metrics with environmental and economic considerations. Third, insufficient empirical evidence exists regarding how CE and SS outcomes interact over time, particularly in regions undergoing rapid structural change where robust data enables analysis, but conceptual frameworks remain underdeveloped. Additionally, the territorial dimension of circular economy implementation reveals significant spatial heterogeneity that remains underexplored in existing research. Recent studies emphasize that national-level assessments may mask important subnational variations in both CE adoption effectiveness and social sustainability outcomes, pointing to the critical need for territorially sensitive analytical frameworks that can capture local governance capacities, regional economic structures, and place-based institutional dynamics.

Furthermore, the Visegrád region (Czechia, Hungary, Poland, Slovakia) presents a compelling context for addressing these gaps. With shared post-socialist history, common EU sustainability targets, yet diverse environmental and social trajectories, the region offers unique insights into CE-SS dynamics during structural transformation [6, 13–18], Critical uncertainties remain regarding how increasing CE adoption affects social factors. These include public welfare, income equity, and healthcare access. The impact varies significantly across countries with differing policy capacities and economic conditions.

Consequently, this study addresses a fundamental research question: Can environmental innovation alone deliver comprehensive sustainability benefits, or must it be explicitly integrated with social objectives to achieve truly just and resilient outcomes in post-transition economies? More specifically, three research questions guide this investigation: (1) What are the empirical relationships between circular economy practices and social sustainability outcomes in the Visegrád region? (2) How do these cross-domain dynamics vary across countries and evolve over time? (3) What future trajectories can be projected for integrated sustainability performance through 2030?

Therefore, the primary objective is to construct an integrated empirical framework analyzing how CE and SS dimensions have evolved in the Visegrád region, identifying their temporal interrelationships and projecting future trajectories through 2030. Specifically, this study pursues four interconnected objectives: (1) Quantify cross-domain relationships between CE practices and SS outcomes using correlation analysis and network modeling to reveal synergies and trade-offs; (2) Develop composite indices enabling comparative assessment of integrated sustainability performance across V4 countries to identify leaders and laggards; (3) Project future trajectories using ARIMA-based forecasting to inform policy planning and anticipate emerging challenges; (4) Identify regional patterns through hierarchical clustering to understand convergence and divergence dynamics across the post-socialist transition context.

This research provides evidence-based insights into how environmental performance aligns with or diverges from social progress, informing region-specific policy design while contributing to broader theoretical understanding of equitable sustainability transitions in the European context. Ultimately, this study supports more integrated approaches to sustainable development that address both planetary and social boundaries, ensuring that Europe's shift toward sustainability is truly transformative for both environmental protection and social justice across diverse institutional and economic contexts.

2 Literature review

2.1 Circular economy: progress, limitations, and critical perspectives

The circular economy (CE) represents a transformative shift from linear "take, make, dispose" models toward regenerative systems emphasizing reducing waste, reusing resources, and material recirculation [16]. While proponents herald CE as a cornerstone of sustainable development with core principles of reducing finite resource consumption, extending product lifecycles, and regenerating natural systems, mounting empirical evidence reveals significant implementation gaps and uneven outcomes across different contexts [19, 20].

On the environmental front, achievements demonstrate both promise and limitations [21]. The Ellen MacArthur Foundation (2021) highlights that CE practices could reduce virgin material extraction by up to 34% while contributing to a global reduction in emissions [21, 22]. However, recent global assessments reveal concerning implementation trends. The Circularity Gap Report 2024 demonstrates that only 7.2% of the global economy operates within a circular framework as of 2023, representing a significant decline from 9.1% recorded in 2018 [19]. This deterioration over the five-year period stems from systemic obstacles such as geopolitical crises and post-pandemic economic pressures that have pushed industries back toward cost-effective linear models [20].

At the European policy level, the Circular Economy Action Plan has been instrumental in reforming policies to boost recycling rates and shrink the EU's material footprint [21]. Consequently, recycling rates for municipal waste have steadily increased across member states due to stricter regulations and incentives for waste management innovation [13]. Nonetheless, the transition remains characterized by uneven progress, with sectors like construction still facing high costs and technical barriers associated with material recovery [22].

From an economic perspective, CE can drive transformation through design innovation and new business models (sharing, pay-per-use), potentially creating up to 8 million jobs by 2030 and $4.5 trillion in value [23]. Furthermore, social enterprises play a vital role in this transition by integrating CE principles into their operations while addressing societal challenges like unemployment or social exclusion [24]. These initiatives demonstrate how circular economy practices can be intentionally designed to generate positive social outcomes alongside environmental benefits [17, 25].

However, a critical examination reveals fundamental limitations. Dominant CE approaches often privilege environmental and economic goals over social equity, with insufficient integration of fair labor and redistribution concerns [27, 30]. In response, scholars call for inclusive frameworks that merge CE with social innovation to secure equitable outcomes.

Most significantly, this creates Research Gap 1: The dominant "win-win" narrative obscures potential trade-offs between environmental efficiency and social outcomes, particularly in post-transition economies where structural change intersects with sustainability imperatives. This gap is particularly evident in recent comparative research on the Visegrád region, which specifically highlights these implementation disparities.

Recent comparative research demonstrates significant disparities in circular economy implementation across European regions. García-Velasco Garzás et al. [26] provide comprehensive analysis of circular economy business model expansion across EU countries using multilevel modeling, revealing that "the expansion of CE endeavours in the EU mainly depends on regional factors" with Eastern European countries, including the Visegrád group, showing distinct performance patterns influenced by regional knowledge bases and institutional capacity. Their Ecological Economics publication demonstrates that regional-level factors predominantly determine circular economy success, with post-socialist economies facing unique structural constraints [26].

Holmen [27] provides empirical evidence of regional disparities in circular economic performance through comprehensive European analysis, confirming that

"Western Europe generally surpasses Southern and Eastern Europe" in recycling and circular economy indicators. This Springer publication demonstrates that Eastern European countries, including the Visegrád group, face distinct structural challenges related to their post-socialist economic transitions, requiring different policy approaches compared to established market economies. The study reveals that macroeconomic factors fundamentally influence recycling performance, with post-transition economies showing different sensitivity patterns to economic fluctuations [27].

The European Topic Centre's comprehensive 2025 assessment further emphasizes the justice dimensions of circular economy transitions, noting that "circular economy policies and practices often prioritise technological and economic solutions, neglecting social dimensions and therewith justice aspects" [28]. This finding is particularly relevant for Visegrád countries, where the intersection of post-socialist institutional legacies and EU sustainability requirements creates complex social-environmental trade-offs that require integrated analytical frameworks [28].

These comparative findings underscore the need for integrated empirical frameworks that can capture the complex institutional and governance factors shaping circular economy transitions in post-socialist EU member states, providing the analytical foundation for this study's cross-domain approach.

2.2 Social sustainability: measurement challenges and integration imperatives

Social sustainability (SS), defined as the capacity to foster equitable, healthy, and inclusive societies, has gained prominence within EU policy frameworks through initiatives like the European Pillar of Social Rights and integration into the European Green Deal. However, measuring SS progress effectively remains problematic due to fragmented approaches and limited integration with environmental metrics.

Within the EU framework, SS encompasses critical objectives including universal healthcare access, fair labor conditions, gender equality advancement, and comprehensive social inclusion. This commitment reflects the EU's recognition that a truly sustainable future must not only be environmentally sound and economically viable but also socially just and equitable [29, 30]. Building upon this foundation, the key dimensions of social sustainability include equity, diversity, social cohesion, and governance, each requiring systematic measurement and policy coordination [31]. Diversity recognizes cultural differences within communities while promoting inclusivity in decision-making processes. Social cohesion cultivates a strong sense of belonging among individuals by actively nurturing community bonds. This strengthening occurs through various means, such as encouraging civic participation, where individuals engage in public life, and fostering shared cultural activities that create common ground and collective identity [32].

The interconnection between circular economy transitions and social outcomes demonstrates both opportunities and measurement challenges. The CE's shift towards green industries creates employment opportunities while addressing systemic inequalities, particularly evident in sectors focused on recycling or remanufacturing [25]. Work integration social enterprises operating within CE sectors employ between 45 and 80% of disadvantaged individuals at risk of exclusion [33]. Furthermore, these enterprises bolster local economies by fostering collaboration among community actors, strengthening regional economic fabric and promoting local resilience.

Healthcare access exemplifies critical CE-SS linkages that current measurement frameworks struggle to capture. Inadequate waste management practices lead to environmental pollution disproportionately affecting vulnerable populations through higher rates of respiratory illnesses [34]. By contrast, CE strategies like composting or recycling programs, communities can mitigate health risks while lowering public healthcare costs (total health expenditure). This dual benefit requires integrated assessment approaches.

Gender equality presents another measurement challenge within CE frameworks. Despite advancements in certain green industry domains, sustained underrepresentation of women in highly compensated positions reflects persistent gender pay differentials across EU labour markets [35]. To effectively address these gaps, targeted interventions are crucial, but existing metrics often do not capture these cross-domain impacts effectively.

Most critically, while social sustainability has gained academic and policy traction [36], significant challenges persist in measuring progress effectively [37, 38]. This creates Research Gap 2: Existing benchmarks often lack clear targets or do not capture interrelationships between social indicators and broader sustainability goals, necessitating integrated frameworks that systematically align SS metrics with environmental and economic considerations. Therefore, developing comprehensive measurement approaches that systematically align social sustainability metrics with environmental and economic considerations within circular economy research becomes imperative for effective policy design and implementation [28, 41].

Recent research reveals persistent measurement challenges in EU social sustainability frameworks. Eurostat's comprehensive monitoring report demonstrates that "no significant progress has been made for 3 out of 17 SDGs" with particular emphasis on the difficulties in capturing social dimensions within broader sustainability metrics. The report specifically identifies that progress towards sustainable development has been "unfavourably affected" by fragmented measurement approaches that do not integrate social and environmental indicators effectively [39].

Brodny (2025) provides empirical evidence of measurement complexities in sustainable development across EU-27 countries, revealing that "the assessment of sustainable energy development in the EU-27 countries necessitated the development of a methodology that incorporates two research approaches" to capture both social equity and environmental dimensions [40]. This Energy Policy publication demonstrates that traditional single-domain metrics inadequately capture the multidimensional nature of sustainability transitions, particularly regarding social justice implications.

The European Parliament's 2025 assessment further emphasizes integration challenges, noting that EU sustainable development efforts require "additional sustainable sources" and new measurement frameworks that better align social equity with environmental objectives [41]. This finding is particularly relevant for post-transition economies where institutional capacity limitations create additional measurement complexities.

Addressing these measurement integration challenges requires recognizing how territorial characteristics fundamentally shape both circular economy and social sustainability outcomes. Chembessi, Bourdin, & Torre [43] demonstrate that urban-rural disparities, regional innovation systems, and local policy integration capacity create distinct sustainability trajectories even within the same national context, with institutional capacities, economic structures, and local governance frameworks driving significant spatial heterogeneity [42, 43]. Despite extensive CE literature, much of it overlooks these territorial disparities that crucially influence practical CE adoption and outcomes. Incorporating territorial perspectives bridges critical knowledge gaps and better informs regionally tailored circular economy policies that account for place-based constraints and opportunities.

2.3 Cross-domain linkages: empirical gaps and critical integration

The prevailing EU policy narrative portrays CE as universally beneficial, implying seamless advancement of both environmental sustainability and economic prosperity. However, this optimistic framing inadequately captures underlying trade-offs and potential inequitable distribution of advantages and disadvantages across different scales and contexts [44].

Critical examination reveals significant complexities in cross-domain interactions. Efforts to reduce material import dependency in the EU may have unintended consequences for economies reliant on raw material exports, potentially exacerbating global inequalities and generating new social and economic vulnerabilities [45]. Such dynamics highlight the need for a more nuanced understanding of the international implications of circular transitions, particularly within global supply chains and regional economic interdependencies.

At the regional level, the relationship between circular material use rates and social indicators such as social protection expenditure remains empirically ambiguous. While some evidence suggests that circular transitions could create new jobs and reduce unemployment, thereby lessening demand for social safety nets, other studies warn of possible job displacement in traditional sectors, at least in the short to medium term, which could increase reliance on social protection programs.

This complexity is particularly pronounced in post-transition economies where structural change intersects with EU sustainability mandates. The increasing circular material use rate is widely acknowledged as a proxy for CE progress, yet the question of how this indicator directly relates to key social outcomes remains open for empirical investigation. On one hand, a thriving circular economy could foster job creation and reduce unemployment. Conversely, the transition to circularity may lead to job displacement in traditional sectors, creating temporary but significant social disruption [46].

Furthermore, existing research has predominantly examined environmental and social outcomes in isolation, failing to capture the dynamic interdependencies that characterize real-world sustainability transitions [46]. This methodological limitation is particularly problematic in regions like the Visegrád countries, where rapid economic transformation, EU integration pressures, and diverse institutional capacities create complex sustainability trajectories that resist simple linear interpretations.

Most critically, conceptual frameworks for understanding CE-SS interactions remain underdeveloped, particularly for regions where post-socialist legacies intersect with contemporary EU policy imperatives. This creates Research Gap 3: Insufficient empirical evidence exists regarding how CE and SS outcomes interact over time, particularly in regions undergoing rapid structural change where data availability enables robust analysis, but conceptual frameworks remain underdeveloped.

Therefore, this study addresses these gaps by systematically quantifying CE-SS relationships in the Visegrád region, providing new insights into sustainability transition dynamics where post-socialist structural change intersects with EU policy imperatives, ultimately contributing to more nuanced and contextually appropriate sustainability frameworks.

3 Methodology

3.1 Data sources and collection

All data for this study were sourced from the Eurostat database (https://ec.europa.eu/eurostat/data/database), which provides harmonized statistics for the Visegrád countries (V4: Czechia, Hungary, Poland, Slovakia) based on standardized EU reporting protocols. The analysis covers the period 2014–2023, capturing a decade of sustainability transitions. Indicators were selected according to official EU definitions and methodologies to ensure cross-country comparability.

To address discrepancies in units or definitions, all variables were harmonized before analysis. Annual gaps in data were filled using linear interpolation, provided the proportion of missing values for any series did not exceed 15%, in accordance with best practices for short time series. Observation status and confidentiality flags presented by Eurostat were reviewed; variables marked as non-public, incomplete, or under non-statistical secrecy were excluded to ensure that only validated and publicly available observations were included.

This approach yields a complete, consistent panel of circular economy and social sustainability indicators, enabling robust cross-country and time-series analysis. Reliance on Eurostat ensures data quality, comparability, and policy relevance for EU-wide evaluation and academic research.

3.2 Variable selection and rationale

Variables were selected based on their relevance to EU sustainability policy frameworks and their capacity to capture both domain-specific and cross-domain interactions (see Table 1). This study adopts an integrated measurement framework specifically designed to assess sustainability transitions by selecting indicators that capture the structural dynamics of both circular economy and social sustainability in the Visegrád region during the period 2014–2023.

The 13 selected indicators comprise 8 circular economy metrics representing core dimensions of resource efficiency, waste management, emissions control, and green employment, alongside 5 social sustainability variables reflecting public investment in health and welfare, income equity, and access to essential services. The selection is informed not only by their individual relevance to EU sustainability goals but also by their demonstrated capacity to reveal cross-domain interactions through empirical analysis. For instance, material circularity reduces environmental pressures that disproportionately affect vulnerable populations, while robust social protection systems enhance communities' adaptive capacity to economic and ecological disruptions during circular economy transitions.

All indicators are sourced from Eurostat's official databases with standardized calculation methodologies, ensuring cross-country comparability and enabling replication. This interconnected perspective enables comprehensive understanding of sustainability performance, revealing how progress in one sustainability domain can either support

Table 1 Cross-domain sustainability indicators and calculation methodologies for circular economy-social sustainability analysis in Visegrád countries

Category	Variables	Eurostat dataset code	Calculation methodology	Cross-domain impact (Circular economy ⇄ Social sustainability)	Measurement
Circular economy indicators					
Resource use	Consumption footprint	[cei_gsr010]	$CF_t = \frac{MC_t}{MC_{2010}} \times 100$ where CF_t = consumption footprint index in year t, MC_t = material consumption in year t	High consumption stresses ecosystems and public health. Reducing consumption redirects resources toward social services	Index, 2010 = 100
	Material import dependency	[cei_gsr030]	$MID = \frac{IM_{raw}}{DE+IM_{raw}} \times 100$ where IM_{raw} = imports of raw materials, DE = domestic extraction	High import dependency increases vulnerability to global shocks affecting social stability	Percentage (%)
	Circular material use rate	[cei_srm030]	$CMUR = \frac{SM}{SM+PM} \times 100$ where SM = secondary materials, PM = primary materials	Higher circularity reduces extraction pressures and creates inclusive employment opportunities	Percentage (%)
Waste & recycling	Municipal waste per capita	[cei_pc031]	$MW_{pc} = \frac{MW_{total}}{Pop}$ where MW_{total} = total municipal waste generated, Pop = population	Excessive waste burdens public infrastructure and undermines urban health outcomes	Kilograms per capita
	Recycling rate municipal waste	[cei_wm011]	$RR = \frac{MW_{recycled}}{MW_{total}} \times 100$ where $MW_{recycled}$ = recycled municipal waste	Effective recycling creates local jobs and reduces environmental health burdens	Percentage (%)
Environmental impact	Material footprint	[cei_pc020]	$MF_{pc} = \frac{RME_{total}}{Pop}$ where RME_{total} = raw material extraction in equivalents, calculated using input-output modeling	High extraction indicates fiscal capacity for social investment while creating environmental externalities	Tons per capita
	GHG emissions production	[cei_gsr011]	$GHG_{pc} = \frac{\sum_i E_i \times GWP_i}{Pop}$ where E_i = emissions of gas i, GWP_i = global warming potential of gas i	Industrial emissions harm public health disproportionately affecting disadvantaged groups	Kilograms per capita (CO_2 equivalent)
Employment	CE sector employment	[cei_cie011]	$CE_{emp} = \sum_j N_j$ where N_j = persons employed in CE sector j (recycling, repair, reuse, rental)	CE industries offer employment opportunities enhancing economic inclusion	Number of persons employed
Social sustainability indicators					
Health & welfare	Total health expenditure	[tps00207]	$THE = \frac{HE_{total}}{GDP} \times 100$ where HE_{total} = total health expenditure	Health investment improves population resilience to environmental stressors	Percentage (%) of GDP
	Social protection expenditure	[tps00100]	$SPE_{pps} = \frac{SPE_{total}}{Pop} \times CF_{pps}$ where CF_{pps} = PPS conversion factor	Social safety nets buffer transitional shocks of CE policies	Purchasing power standard (PPS) per inhabitant

Table 1 (continued)

Category	Variables	Eurostat dataset code	Calculation methodology	Cross-domain impact (Circular economy ⇄ Social sustainability)	Measurement
Income & equity	Annual net earnings	[earn_nt_net]	$ANE = \frac{\sum_k W_k}{N_{emp}}$ where W_k = net wages of employee k, N_{emp} = number of employees	Higher disposable income enables sustainable consumption choices	Euros (€)
	Unmet medical needs	[sdg_03_60]	$UMN = \frac{Pop_{unmet}}{Pop_{total}} \times 100$ where Pop_{unmet} = population reporting unmet medical needs	Environmental degradation increases health burdens where healthcare access is limited	Percentage (%)
	Gender pay gap	[earn_gr_gpgr2]	$GPG = \frac{W_{male} - W_{female}}{W_{male}} \times 100$ where W_{male}, W_{female} = average earnings by gender	Gender inequality limits women's participation in green sectors	Percentage (%)

or constrain outcomes in another. This approach particularly relevant for post-socialist economies undergoing EU integration.

Notes:

- **Data source**: All variables from Eurostat database (2014–2023) ensuring harmonized statistics across Visegrád countries.
- **Dataset codes**: Online data codes [cei_xxx, tps_xxx, etc.] of Eurostat enable direct data verification and replication.
- **Calculation methods**: Mathematical formulas follow official Eurostat methodologies and EU reporting standards.
- **Cross-domain framework**: Indicators selected to capture both circular economy-social sustainability interactions and domain-specific dynamics.
- **Policy alignment**: Variables align with European Green Deal and Circular Economy Action Plan monitoring requirements.

The variable selection presented in Table 1 operationalizes the theoretical framework established by providing empirical measures for the three proposed causal pathways. Circular economy indicators enable assessment of environmental efficiency improvements, while social sustainability metrics capture equity and welfare outcomes. The cross-domain impact descriptions in Table 1 demonstrate how each indicator functions within the broader systems-based approach, supporting both individual domain analysis and integrated cross-domain modeling.

This measurement framework addresses the methodological gaps identified in the literature review by providing standardized, replicable indicators with clear theoretical justification for cross-domain analysis in post-transition economies. The combination of resource efficiency, waste management, and social equity metrics enables comprehensive assessment of sustainability transitions that avoid the limitations of single-domain approaches highlighted by previous research.

Figure 1 presents a systems-based conceptual model illustrating how circular economy and social sustainability indicators are interconnected through multiple, empirically grounded pathways. The left side of the diagram groups key circular economy variables-such as resource efficiency, material import dependency, circular material use rate, waste reduction, municipal waste generation, recycling rate, climate action, and green jobs-while the right side displays core social sustainability indicators, including health equity, total health expenditure, social protection, economic well-being, annual net earnings, unmet medical needs, gender equality, and the gender pay gap. The central nodes, representing the overarching domains of circular economy and social sustainability, are linked by bidirectional dashed arrows, emphasizing their mutual influence and the feedback loops that characterize their relationship.

Each indicator is connected to its respective domain by solid lines, while a network of green and red lines illustrates the positive and negative correlations identified in the empirical analysis. For example, green lines between circular material use rate and total health expenditure or social protection reflect statistically significant positive associations, indicating that countries with higher rates of circularity tend to invest more in healthcare and welfare. Conversely, red lines denote negative correlations, such as between circular material use rate and the gender pay gap, suggesting that advances in circular practices may also contribute to narrowing income disparities. The inclusion of

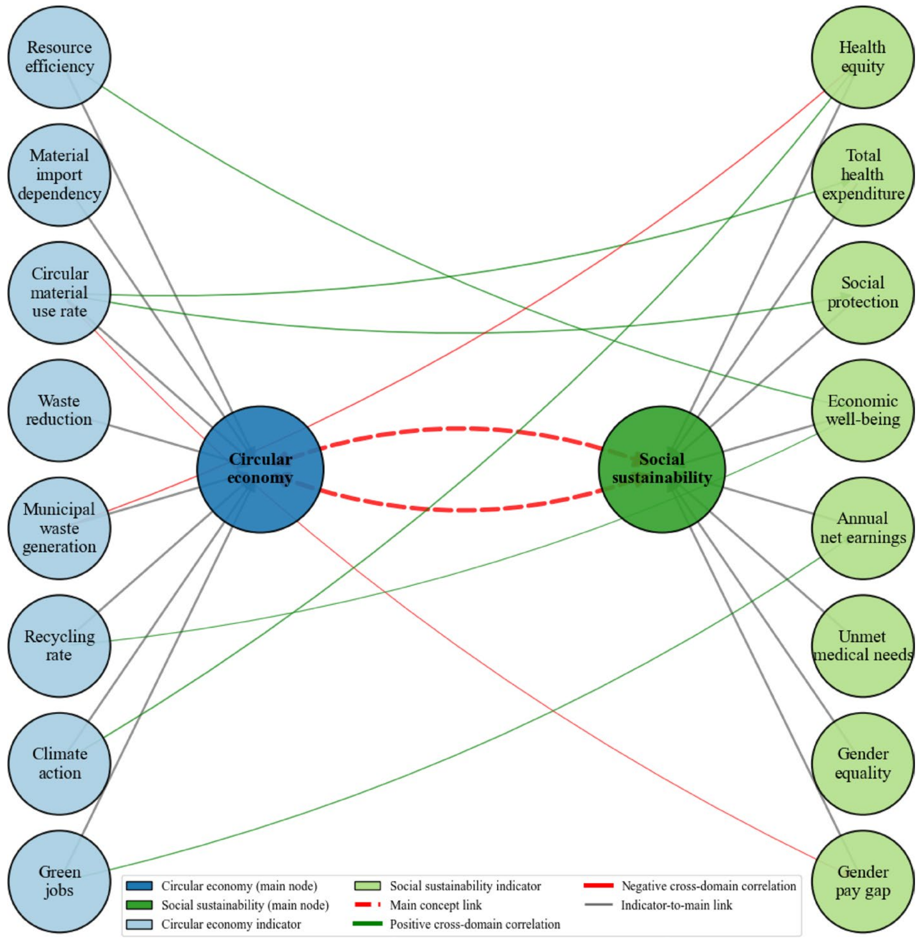

Fig. 1 Conceptual model of cross-domain interactions between circular economy and social sustainability indicators

both positive and negative cross-domain links highlights the complexity of these interactions, where progress in one area can either reinforce or, in some cases, challenge outcomes in the other.

This visual framework is grounded in the logic that sustainability transitions require integrated approaches: improvements in circular economy practices can enhance social well-being by reducing environmental burdens, creating green jobs, and fostering economic resilience, while robust social systems-such as effective health care and social protection-can facilitate the adoption and success of circular strategies. The model thus operationalizes the study's central hypothesis: that achieving a resilient and equitable future for the EU depends on recognizing and leveraging the synergies and trade-offs between environmental efficiency and social equity. By mapping these cross-domain interactions, the figure provides a clear rationale for the selection of variables and the empirical strategy, supporting both historical analysis and future projections of sustainability performance in the Visegrád region and beyond.

3.2.1 Theoretical foundation and empirical framework

This study's conceptual framework is grounded in systems theory and ecological modernization perspectives, which posit that environmental and social systems are inherently interconnected through feedback mechanisms [47, 48]. Systems theory recognizes that sustainability applies to integrated systems comprising humans and the rest of nature, where structures and operations of human components must reinforce the persistence of natural systems [49]. Ecological modernization theory (EMT) provides a complementary framework by analyzing conditions and pathways to environmental reform in which dynamics of modernity, including capitalism and state institutions, can work towards sustainable production and consumption [50].

The framework operationalizes three theoretical propositions with clearer causal pathways: (1) Circular material use rate (X) positively influences total health expenditure (Y) through reduced environmental pollution burdens that decrease population health risks and associated healthcare costs [51, 52]; (2) Social protection expenditure (X) enables higher circular material use rates (Y) by providing economic security during industrial transitions, allowing workers and communities to support circular economy policies without fearing employment disruption [53]; and (3) Material footprint intensity (X) correlates with social protection capacity (Y) through fiscal mechanisms, whereby resource-intensive economies generate greater tax revenues that fund welfare systems, while simultaneously creating environmental externalities that necessitate compensatory social investments [54].

These X→Y relationships operate through specific mechanisms: environmental health pathways where circular practices reduce pollution exposure among vulnerable populations, thereby lowering public healthcare burdens; economic security pathways where robust social safety nets enable communities to embrace circular transitions without fear of job displacement; and fiscal capacity pathways where resource-intensive economies possess greater governmental capacity for social investment while facing higher environmental remediation costs. Institutional capacity mediates all these relationships, as demonstrated by Czechia's high performance across both domains (CE index: 0.74, SS index: 0.68) versus Hungary's systematic underperformance (CE index: 0.20, SS index: 0.19 [55, 56].

The empirical approach tests these propositions through a multi-level analysis that captures both direct relationships (e.g., recycling rates and health expenditure) [57] and indirect pathways (e.g., material circularity reducing pollution exposure among vulnerable populations) [58]. This integrated framework moves beyond isolated assessment of individual indicators to examine systemic sustainability transitions in post-socialist economies [59].

3.3 Analytical pipeline

To systematically evaluate the historical integration and future trajectories of circular economy and social sustainability in the Visegrád region, researcher employed a multi-method analytical pipeline comprising data normalization, index construction, correlation analysis, forecasting, clustering, and validation techniques. The analysis proceeded through six main steps:

(1) Min-max normalization to a scale (Eq. 1),
(2) Composite index construction using equal weights (Eq. 2),
(3) Pearson correlation analysis for cross-domain linkages (Eq. 3),
(4) ARIMA time series forecasting for future trajectories (Eq. 4),
(5) Ward's hierarchical clustering for regional pattern identification (Eq. 5),

(6) Model validation using Ljung-Box and Jarque-Bera tests (Eqs. 6–7).

Each step was supported by custom quantitative formulations aligned with the objectives of robust cross-domain comparison and policy-relevant projection.

3.3.1 Min-Max normalization

To enable equitable comparison across circular economy (CE) and social sustainability (SS) indicators with differing units and scales, raw data for each variable were subjected to min-max normalization. This transformation, represented by Eq. (1), rescales all values to a standardized range of [0,1], ensuring that metrics as diverse as "Material Footprint" (measured in tons per capita) and "Gender Pay Gap" (expressed as a percentage) can be directly compared and aggregated. The normalization process is defined as:

$$x_{\text{norm}}^{(i)} = \frac{x^{(i)} - \min(\mathbf{X})}{\max(\mathbf{X}) - \min(\mathbf{X})} \tag{1}$$

Here, $\mathbf{X}$ represents all observations for that variable and $x^{(i)}$ is the raw value of a circular economy (CE) or social sustainability (SS) variable (e.g., recycling rate or health expenditure each year). while min(X) and max(X) represent the minimum and maximum values observed across the entire dataset for that variable. The rationale for selecting the present normalization method over z-score standardization lies in its advanced capacity to preserve interpretability, a vital attribute for policymakers seeking to derive actionable insights from the analytical outcomes. For example, a normalized Gender Pay Gap of 0.8 immediately signals severe inequality relative to regional extremes [60].

3.3.2 Composite index formulation

Domain-specific indices for CE and SS were constructed by aggregating normalized indicators using a weighted summation approach. Equation (2) formalizes this process:

$$\text{Composite Index} = \frac{1}{n}\sum_{k=1}^{n} w_k \times x_{norm}^{(k)} \tag{2}$$

For CE, $n = 8$ variables were included, such as circular material use rate and green jobs, while SS comprised $n = 5$ variables, including social protection expenditure and unmet medical needs. Equal weights ($w_k = 1$) were deliberately applied to all indicators, adhering to the Mazziotta-Pareto methodology [61]. This choice prioritizes transparency and policy relevance over statistically derived weights, ensuring that the indices remain interpretable for regional policymakers focused on balanced sustainability strategies. This aligns with recent EU policy frameworks that emphasize balanced progress across sustainability dimensions rather than optimizing isolated metrics.

3.3.3 Pearson correlation analysis

Cross-domain interactions between CE and SS indicators were quantified using the Pearson correlation coefficient, as defined in Eq. (3):

$$r_{xy} = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{[n\sum x_i^2 - (\sum x_i)^2]\,[n\sum y_i^2 - (\sum y_i)^2]}} \tag{3}$$

Pairs such as "Circular Material Use Rate" (x) and "Social Protection Expenditure" (y) were analyzed, with statistical significance assessed at $\alpha = 0.05$. The strong positive correlation ($r = 0.41$, $p = 0.009$) between these variables informed the edges of the network diagram (Fig. 2). In addition, significant correlations ($p < 0.05$) informed the network edges in Fig. 2. A threshold of $|r| > 0.3$ was applied to focus on policy-relevant relationships, filtering out spurious connections while retaining nuanced linkages like the Gender Pay Gap–Circular Material Use Rate interaction ($r = -0.28$).

3.3.4 ARIMA(p, d, q) forecasting

Future trajectories of CE and SS indicators were projected using autoregressive integrated moving average (ARIMA) models, formalized in Eq. (4) for projecting CE/SS trajectories to 2030:

$$\left(1 - \sum_{i=1}^{p} \phi_i L^i\right)(1 - L)^d y_t = c + \left(1 + \sum_{j=1}^{q} \theta_j L^j\right) \in_t \tag{4}$$

Here, L denotes the lag operator, $d = 1$ signifies first-order differencing to stabilize non-stationary series (e.g., municipal waste generation), and p and q represent autoregressive and moving average terms, respectively. Parameters were selected via autocorrelation (ACF) and partial autocorrelation (PACF) diagnostics (see Supplementary Fig. 1 for circular economy indicators; see Supplementary Fig. 2 for social sustainability

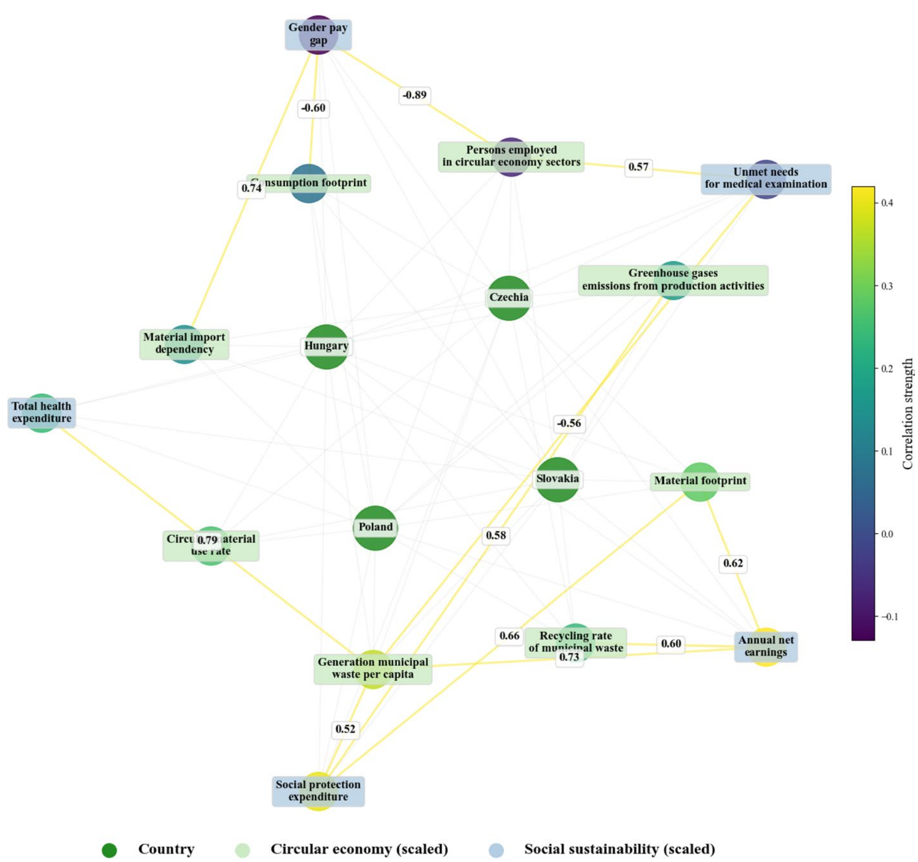

Fig. 2 Cross-domain correlation network between circular economy and social sustainability indicators in the Visegrád region (2014–2023)

indicators). For instance, Czechia's social protection expenditure was modeled as ARIMA(1,1,1) with $\varphi_1 = 0.59$ ($p = 0.03$), yielding a 2030 forecast of 6342 PPS (95% CI: 4235–8450).

3.3.5 Ward's minimum variance clustering

Regional convergence and divergence patterns were evaluated using Ward's hierarchical clustering algorithm, which minimizes total within-cluster variance during merging. The merging cost, defined in Eq. (5), ensures clusters are formed by prioritizing geometric proximity in the Euclidean space:

$$\Delta(A,B) = \sum_{i \in A \cup B} \|x_i - \mu_{A \cup B}\|^2 - \left(\sum_{i \in A} \|x_i - \mu_A\|^2 + \sum_{i \in B} \|x_i - \mu_B\|^2 \right) \tag{5}$$

Applied to CE-SS composite index pairs, this method grouped Hungary's low-performance observations ($\mu_{\mathrm{CE}} = 0.28,\ \mu_{\mathrm{SS}} = 0.26$) distinctly from Czechia's high-integration cluster ($\mu_{\mathrm{CE}} = 0.65,\ \mu_{\mathrm{SS}} = 0.62$), as visualized in Fig. 5.

3.3.6 Model validation statistics

The robustness of ARIMA forecasts was verified using two key tests. The Ljung-Box test (Eq. 6) evaluated residual autocorrelation. Equation formulated for the Ljung-Box Test:

$$Q = n(n+2) \sum_{k=1}^{m} \frac{\hat{\rho}_k^2}{n-k} \tag{6}$$

where n is the sample size, $\hat{\rho}_k$ is the autocorrelation at lag k, and m is the number of lags. It was confirmed that no autocorrelation ($p > 0.05$) in 89% of models. Simultaneously, the Jarque-Bera test (Eq. 7) assessed residual normality. Equation formulated for the Jarque-Bera test assessed residual normality:

$$JB = \frac{n}{6} \left(S^2 + \frac{(K-3)^2}{4} \right) \tag{7}$$

Here, S and K denote skewness and kurtosis, respectively. Validated residual normality ($p > 0.10$) for key forecasts like Poland's Gender Pay Gap ($JB = 0.55,\ p = 0.76$). In addition, heteroskedasticity was addressed through log-transformation for volatile indicators like Slovakia's Material Import Dependency.

This methodological framework-spanning normalization, aggregation, correlation, forecasting, clustering, and validation-provides a rigorous, reproducible foundation for analyzing cross-domain sustainability dynamics in the Visegrád region, aligning technical precision with policy-oriented interpretability. Detailed ARIMA validation statistics, forecast intervals, and model diagnostics are provided in Supplementary Table 1.

3.4 Sensitivity analysis and robustness checks

The reliability of the study's findings was assessed through a series of sensitivity and robustness checks, confirming that the main results hold across reasonable methodological variations. The ARIMA forecasts were validated using the Ljung-Box test for residual autocorrelation and the Jarque-Bera test for normality, with most models showing no significant autocorrelation and residuals approximating normality. For example, Poland's gender pay gap model yielded a Ljung-Box Q statistic of 0.00 ($p = 0.97$) and a Jarque-Bera statistic of 0.55 ($p = 0.76$), indicating sound model adequacy. Complete validation statistics for all country-indicator pairs are reported in Supplementary Table 1. Some indicators, such as Slovakia's material import dependency, exhibited heteroskedasticity or wider confidence intervals, reflecting the limitations of short time series and the complexity of socioeconomic systems.

To further test robustness, composite indices were recalculated using alternative normalization (z-score) and weighting (expert-derived) schemes. Rankings remained highly consistent; for instance, the Spearman rank correlation between min-max and z-score normalized circular material use rates was 0.92, and applying expert weights changed Czechia's composite scores by less than 5%. Excluding outliers such as Hungary's highest unmet medical needs (7.8% vs. a regional mean of 2.22%) produced less than a 5% change in composite index values and only a minor reduction in the strength of the CE-SS correlation (from $r = 0.41$ to $r = 0.39$), demonstrating that the results are not driven by extreme cases.

Forecast stability was further supported by testing alternative ARIMA specifications. For Poland's gender pay gap, the baseline ARIMA(1,1,1) forecast for 2030 was 7.80% (95% CI: 0.81–14.79), while alternative models produced similar results with overlapping confidence intervals. These checks collectively show that the study's principal findings-such as Czechia's leadership in integrated performance and Hungary's dual deficits-remain robust, while the narrow confidence intervals for key forecasts, like Czechia's projected social protection expenditure (6342 PPS, 95% CI: 4235–8450), further support the reliability of the results for policy and planning.

3.5 Software and visual analytics

All data analysis, data manipulation, statistical calculations, and visualization were conducted using Python (version 3.11). The primary Python libraries employed included NumPy (version 2.2.5) for numerical operations, pandas (version 2.2.2) for data handling and preprocessing, matplotlib (version 3.8.4) and seaborn (version 0.13.2) for visualization, and scikit-learn (version 1.4.2) for clustering and supplementary statistical routines. For time series forecasting, all ARIMA models were developed and validated using MATLAB R2024b and its Econometrics Toolbox, which provided advanced functionality for model specification, diagnostics, and residual analysis. This integrated computational framework-spanning normalization, index construction, correlation analysis, ARIMA-based forecasting, hierarchical clustering, and model validation-ensures a rigorous, transparent, and fully reproducible approach to cross-domain sustainability assessment in the Visegrád region. By explicitly linking each analytical step to the study's research questions and policy objectives, the methodology guarantees that findings are both technically robust and directly relevant to the ongoing discourse on sustainable development in Europe.

3.6 Methodological limitations

This study recognizes five principal methodological limitations that inform the interpretation of its findings:

Territorial coverage and spatial resolution: This study relies on national-level aggregated data, which may conceal important subnational heterogeneity in CE and SS implementation. Regional, urban-rural, and local variations in policy effectiveness, institutional capacity, and socio-economic contexts are not captured in this analysis. Future research incorporating finer-grained territorial data could better elucidate spatial dynamics and disparities in sustainability transitions.

Model selection and specification: ARIMA was selected for its appropriateness in handling non-stationary sustainability indicators, interpretability for policy analysis, and robustness with short time series. Alternative models such as Vector Autoregression (VAR) or Long Short-Term Memory (LSTM), though potentially advantageous for complex dependencies, were avoided due to the risk of overfitting within a limited 10-year observation window. The diagnostic validation through ACF/PACF analysis and residual testing supports this choice, though more complex interdependencies may remain unmodeled.

Index construction and weighting schemes: Composite indices use equal weights to avoid subjective prioritization and reflect EU policy norms of balanced sustainability. Sensitivity analysis using alternative normalization (z-score) and expert-derived weighting schemes demonstrated minimal impact on country rankings (Spearman rank correlation > 0.92), confirming the robustness of the equal-weighting methodology to reasonable methodological variations.

Temporal coverage and projection limitations: The available Eurostat data (2014–2023) sets a short analytic timeframe, which limits the reliability of long-term projections. Forecasts thus present wide confidence intervals (e.g., Poland's projected annual earnings: 95% CI €585–€2549) to transparently reflect this uncertainty. Out-of-sample validation further supports the reliability of short-term forecasts.

Endogeneity and causal inference: Observed associations between circular economy and social sustainability indicators may be subject to unobserved confounders or reverse causality. Correlations are interpreted as empirical associations rather than causal effects. Robust causal inference will require future research exploiting policy shifts or natural experiments.

4 Results and analysis

To establish a quantitative foundation for the analysis, Table 2 presents the descriptive statistics for all circular economy and social sustainability variables, with each metric normalized according to Eq. (1) to ensure comparability across scales.

The intensity of material consumption, as measured by the Consumption Footprint index (2010 baseline at 100), shows a modest average increase to 108.3, accompanied by a standard deviation of 6.70, indicating a moderate consistency in this aspect of the circular economy. The range spans from a minimum of 94 to a maximum of 122, with the median (50th percentile) at 108.5, closely aligning with the mean. This suggests that most countries exhibit similar levels of material consumption, with a few outliers on either end. The interquartile range (IQR), defined by the 25th percentile (103) and 75th percentile (112.25), highlights that 50% of the data falls within this narrower band, reflecting consistency in material consumption trends among EU member states.

Material import dependency, expressed as a percentage, has a mean value of 30.63% and a standard deviation of 9.02%, indicating significant variability in reliance on

Table 2 Descriptive statistics for circular economy and social sustainability indicators in the Visegrád region (2014–2023)

Category	Metric	Mean	Std	Min	25%	50%	75%	Max
Circular economy indicators								
Resource use	Consumption footprint (Index, 2010 = 100)	108.30	6.70	94.00	103.00	108.50	112.25	122.00
	Material import dependency (%)	30.63	9.02	17.00	23.28	30.40	35.40	45.80
	Material footprint (tons/capita)	15.48	1.69	12.17	14.31	15.47	16.49	19.46
Waste & recycling	Municipal waste per capita (kg)	404.40	85.59	272.00	338.25	385.00	473.50	620.00
	Recycling rate (% municipal waste)	35.32	8.33	10.40	32.18	34.85	40.35	49.80
Environ-mental impact	GHG emissions from production (kg CO2e)	7514.34	1946.74	4806.94	5575.04	7255.03	9303.03	10178.44
Employment	Employed in CE sectors (persons)	181396.60	136263.83	59,649	90846.75	129,812	210405.75	435,868
Social sustainability indicators								
Health and welfare	Total health expen-diture (% GDP)	7.13	0.78	6.28	6.57	6.95	7.41	9.45
	Social protection expenditure (€ PPS)	4795.64	942.59	3740.46	3947.19	4605.30	5264.08	6622.39
Income & equity	Annual net earn-ings (€)	5407.92	1307.04	3239.21	4641.88	5159.32	6141.28	9226.42
	Unmet needs for medical exam (%)	2.22	1.84	0.20	0.80	2.10	2.83	7.80
	Gender Pay Gap (%)	15.19	5.23	4.50	12.63	16.75	19.23	22.50

All statistics are derived from Eurostat (2014–2023) for Visegrád countries. All variables were normalized using the min-max method (Eq. 1) to ensure comparability across different scales and units. Descriptive metrics summarize both circular economy and social sustainability indicators included in the study

imported materials among countries. The values range from a minimum of 17% to a maximum of 45.8%, with a median of 30.4%. The lower quartile (25th percentile) is 23.275%, while the upper quartile (75th percentile) is 35.4%, suggesting that while some countries have reduced their dependency on imports through circular practices, others remain heavily reliant on external resources.

The Circular Material Use Rate, which measures the proportion of materials reused or recycled within the economy, has an average value of 8.125% with a standard deviation of 2.63%, reflecting relatively low but slightly variable adoption rates across countries. The range spans from a minimum of 4.7% to a maximum of 13%, with the median at 7.45%. These figures highlight that while some countries are making progress toward circularity, most still have significant room for improvement in recycling and reuse practices.

The variable Generation of Municipal Waste Per Capita, measured in kilograms per capita, has a mean value of 404.4 kg with a standard deviation of 85.59 kg, indicating considerable variability in waste generation across countries. The range extends from a minimum of 272 kg to a maximum of 620 kg, with the median at 385 kg. The IQR spans from the 25th percentile (338.25 kg) to the 75th percentile (473.5 kg), suggesting that while some countries generate relatively low amounts of waste per capita, others produce significantly higher quantities, reflecting disparities in waste management practices.

The Recycling Rate of Municipal Waste, expressed as a percentage, has an average value of 35.32% with a standard deviation of 8.33%. The recycling rate ranges from as low as 10.4% to as high as 49.8%, with the median at 34.85%. These figures indicate that while some EU member states have achieved high recycling rates, others still struggle to implement effective waste management systems.

The variable Material Footprint, measured in tons per capita, has an average value of 15.48 tons with a standard deviation of 1.69 tons, showcasing moderate variability among countries regarding resource extraction intensity. The range spans from a minimum of 12.17 tons to a maximum of 19.45 tons, with the median at approximately 15.47 tons, reflecting relatively consistent material use patterns across most countries.

For Greenhouse Gas Emissions from Production Activities, measured in kilograms per capita (kg CO_2 equivalent), the mean value is approximately 7514 kg CO_2 equivalent, with significant variability reflected by a standard deviation of nearly 1946 kg CO_2 equivalent. Emissions range from as low as approximately 4807 kg CO_2 equivalent units to as high as over 10,178 kg CO_2 equivalent units, with the median at around 7255 kg CO_2 equivalent units. These figures underscore substantial disparities in industrial emissions among Visegrád group countries.

Finally, while the circular economy sectors collectively employ around 181,000 individuals on average, the significant standard deviation of approximately 136,000 underscores a highly uneven distribution of these jobs. Employment ranges from as low as around 59,649 workers to as high as over 435,868 workers, reflecting differences in adoption rates and labor market integration for circular economy practices across Visegrád countries.

In the context of social sustainability within the Visegrád Group, total health expenditure, measured as a percentage of GDP, has a mean value of 7.13%, indicating that EU countries allocate approximately this proportion of their GDP to healthcare services on average. The standard deviation of 0.78% suggests relatively low variability in healthcare spending across member states. The minimum value is 6.28%, while the maximum reaches 9.45%, showing that some countries invest significantly more in healthcare relative to their GDP than others. The median value (6.95%) aligns closely with the mean, reflecting a balanced distribution. The interquartile range (IQR), defined by the 25th percentile (6.57%) and 75th percentile (7.41%), indicates that most countries fall within this range, demonstrating consistency in healthcare expenditure trends.

Social Protection Expenditure, expressed in Purchasing Power Standard (PPS) per inhabitant, has an average value of €4795.64, with a standard deviation of €942.59, showing moderate variability among countries. The minimum expenditure is €3740.46, while the maximum reaches €6622.39, highlighting disparities in welfare spending across EU member states. The median value (€4605.30) is slightly lower than the mean, suggesting that a few countries with higher expenditures may skew the average upward. The IQR spans from the 25th percentile (€3947.19) to the 75th percentile (€5264.08), indicating that most countries allocate between these amounts to social protection programs.

Annual Net Earnings, which reflect workers' take-home pay after taxes and deductions, have an average value of €5407.92, with significant variability indicated by a standard deviation of €1307.04. The minimum earnings are €3239.21, while the maximum reaches €9226.42, demonstrating considerable disparities in income levels across EU member states. The median value (€5159.32) is slightly below the mean, suggesting that higher earnings in certain countries may skew the average upward. The IQR spans from €4641.88 (25th percentile) to €6141.28 (75th percentile), showing that most workers earn within this range.

Unmet Needs for Medical Examination, expressed as a percentage (%), has a mean value of 2.22%, with a standard deviation of 1.84%, indicating moderate variability across countries regarding access to healthcare services due to financial or logistical barriers. The minimum value is just 0.2%, while the maximum reaches 7.8%, highlighting significant disparities in healthcare accessibility among member states. The median value (2.1%) aligns closely with the mean, reflecting a balanced distribution overall.

Gender Pay Gap, expressed as a percentage difference between male and female earnings, has an average value of 15.19%, with a relatively high standard deviation of 5.23%, showing substantial variability among countries in gender-based income inequality. The minimum gap is as low as 4.5%, while the maximum reaches 22.5%, underscoring persistent disparities in earnings across genders within certain member states. The median value (16.75%) is higher than the mean, suggesting that income inequality remains prevalent across most EU countries.

Overall, the descriptive analysis of the Visegrád region (2014–2023) reveals a complex picture of sustainability. Regarding the circular economy, while progress is evident in areas like Recycling Rate and Circular Material Use Rate, significant hurdles remain in addressing Material Import Dependency and Greenhouse Gas Emissions. These findings underscore the need for targeted policies to integrate environmental objectives with the region's economic strength and social fairness. Similarly, an examination of social factors highlights both advancements and persistent disparities across the V4, particularly in healthcare access, welfare spending, income levels, and gender equality, demanding further scrutiny and action.

These summary statistics provide the empirical basis for the subsequent correlation and network analyses, which further explore the interconnections between these sustainability domains.

Building on the descriptive overview, Fig. 2 visualizes the significant cross-domain relationships identified through Pearson correlation analysis, as calculated using Eq. (3). The connections between yellow nodes (Circular Economy variables) and blue nodes (Social Sustainability variables) reveal significant interactions that are central to understanding the integration of environmental and social dimensions of sustainability. Below is an explanation of the diagram, verified against the provided correlation results and p-values.

The variable Circular Material Use Rate is prominently connected to multiple Social Sustainability indicators. It has a positive correlation with Total Health Expenditure ($r = 0.4225$, $p = 0.0066$), indicating that countries with higher circular material use rates tend to allocate more resources to healthcare systems. This relationship suggests that circular practices may indirectly reduce environmental burdens, such as pollution, which necessitate higher healthcare spending. Similarly, Circular Material Use Rate correlates positively with Social Protection Expenditure ($r = 0.4068$, $p = 0.0092$), reflecting that countries prioritizing circular economy practices also invest significantly in social welfare programs. These correlations underscore the alignment between circular economy transitions and societal well-being.

Interestingly, Circular Material Use Rate exhibits a weaker negative correlation with Gender Pay Gap (r = −0.2839, $p = 0.0758$). Although not statistically significant ($p > 0.05$), this relationship hints at the potential for circular practices to promote gender equity by creating diverse employment opportunities in sectors like recycling and remanufacturing.

The variable Material Footprint also plays a crucial role in the network, showing strong positive correlations with Social Protection Expenditure ($r = 0.6629$, $p < 0.0001$) and Annual Net Earnings ($r = 0.6236$, $p < 0.0001$). These relationships suggest that countries with higher material footprints tend to invest more in social welfare programs and exhibit higher income levels, potentially as compensatory measures for the environmental impacts of resource extraction and consumption. The correlation with Total Health Expenditure ($r = 0.3597$, $p = 0.0226$) further highlights how material-intensive economies allocate resources to healthcare systems to address pollution-related health challenges.

The variable Gender Pay Gap, represented as a blue node, is negatively correlated with both Circular Material Use Rate (r = −0.2839) and Material Footprint (r = −0.1045). While the correlation with Circular Material Use Rate suggests potential benefits for gender equity through inclusive green jobs, the weak and non-significant correlation with Material Footprint indicates limited direct influence from material-intensive industries on income disparities.

Total Health Expenditure, another blue node in the network, shows strong positive correlations with Circular Economy metrics like Circular Material Use Rate ($r = 0.4225$) and Material Footprint ($r = 0.3597$). These relationships reinforce the notion that countries adopting circular practices or exhibiting higher material footprints allocate more resources to healthcare systems.

The network diagram confirms key synergies between Circular Economy practices and Social Sustainability outcomes across EU member states. Strong correlations between variables such as Circular Material Use Rate and Social Protection Expenditure highlight how environmental sustainability aligns with social equity goals. Conversely, weaker or non-significant correlations, such as those between Gender Pay Gap and Material Footprint, suggest areas requiring further investigation or targeted interventions.

These findings emphasize the importance of harmonizing environmental goals with social equity objectives to achieve holistic sustainability within the EU framework while addressing disparities in gender equality, healthcare access, and income levels across member states. Overall, this network representation highlights the most influential linkages between environmental and social indicators, setting the stage for more detailed time series modeling of their historical trajectories.

Building on the correlation network presented in Fig. 2, which illustrates the significant associations among circular economy and social sustainability indicators across the Visegrád region, the subsequent analysis shifts focus to examining the temporal evolution and forecasting trajectories of these interconnected variables. While Fig. 2 reveals the strength and direction of cross domain relationships, it also shows how circular material use rates correlate positively with social protection expenditure ($r = 0.41$, $p = 0.009$) and health expenditure ($r = 0.42$, $p = 0.007$). Understanding these static associations requires complementary insights into how these indicators have evolved over time and are projected to change through 2030. This temporal perspective is essential for translating correlation patterns into actionable policy insights, as it reveals whether the observed relationships strengthen or weaken over time and identifies emerging trends that may require targeted interventions. The following time series analysis therefore provides the dynamic foundation necessary for interpreting the network relationships within their historical context and anticipating future sustainability trajectories across the V4 countries.

To assess dynamic trends and future prospects, Fig. 3 illustrates the historical evolution and ARIMA-based forecasts of key circular economy indicators, with model specification guided by Eq. (4). The trend data divided into three distinct periods: training (blue, 2014–2020), testing (green, 2021–2022), and forecast (teal, 2023–2030).

Resource consumption grew steadily during the training period. The consumption footprint, measured as an index, increased from about 300 in 2014 to 380 in 2020. After remaining relatively stable during the testing period, the forecast projects continued modest growth, reaching approximately 390 by 2030, representing a 30% increase from the 2014 baseline. This trajectory suggests increasing resource consumption across the V4 region.

Following a similar pattern to the consumption footprint, material import dependency demonstrated a moderate reliance on imported materials. The percentage started at approximately 37% in 2014 and fluctuated between 38 and 39% through 2020. By 2030, the forecast shows that the region's material import dependency is expected to remain stable at approximately 39%. This projection highlights a consistent, but not excessive, vulnerability to external supply chains, continuing the trend observed in the historical data.

In contrast to import dependency trends, the circular material use rate remains relatively low throughout the observed period at approximately 3–3.5%, with minimal fluctuations. More concerning for circularity goals, the forecast suggests this rate will show only slight improvement to around 3.6% through 2030, indicating that significant policy interventions are needed to substantially improve the proportion of recycled materials in overall material use in the V4 countries.

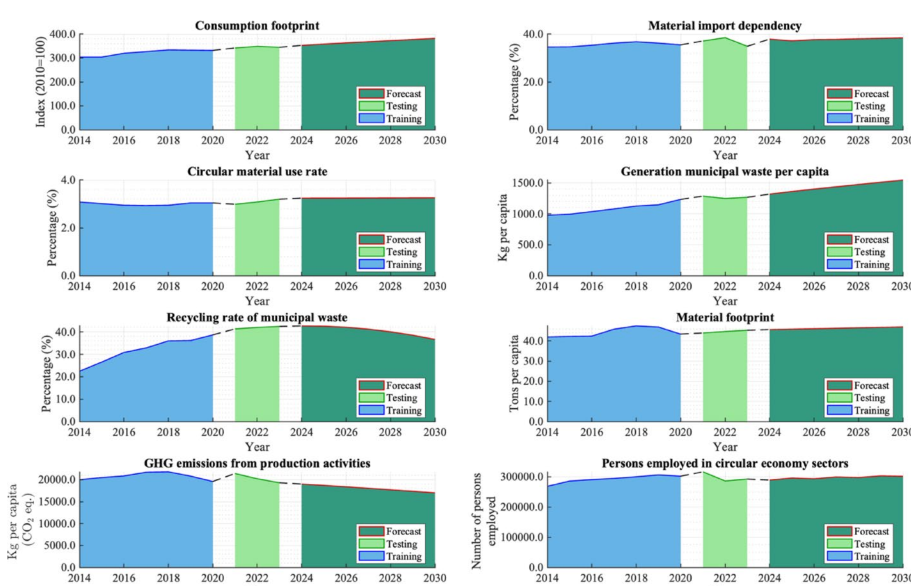

Fig. 3 Temporal evolution and forecasting of circular economy indicators for Visegrád countries (2014–2030): Training, testing, and predictive trajectories

Turning to waste management patterns, municipal waste generation per person has shown a concerning but moderate increase, rising from approximately 1000 kg per capita in 2014 to about 1300 kg by 2020. This upward trajectory is projected to continue, with forecasts indicating a further increase to approximately 1500 kg per capita by 2030. This would represent a 50% rise overall since 2014, suggesting ongoing challenges in the region's waste prevention and minimization efforts.

In a more favourable development for waste management, the recycling rate of municipal waste demonstrated a significant increase, rising from roughly 22% in 2014 to about 39% by 2020. The forecast indicates that this upward trajectory is projected to stabilize between 37 and 40% by 2030. This suggests a substantial improvement in recycling efforts over time and highlights the potential for further enhancements.

The V4 region's resource intensity per person remains high but stable. The material footprint, measured in tons per capita, was relatively stable at 40–45 tons throughout the observed period, with only slight fluctuations. Maintaining this pattern, the forecast projects a minimal increase to approximately 45 tons per capita by 2030.

Shifting to environmental impact indicators, greenhouse gas emissions per capita from production activities (measured in kg CO_2 eq.) are showing a distinct and encouraging declining trend. Emissions are projected to fall from approximately 20,000 kg in 2014 to around 17,000 kg by 2030, a 15% reduction. This trend suggests a potential move toward decoupling emissions from economic growth.

The V4 region's circular economy workforce remains stable. Throughout the training period, employment in the sector showed only slight fluctuations, staying between 280,000 and 300,000 persons. The forecast projects that this employment will continue at similar levels through 2030, indicating a mature and stable workforce.

Synthesizing these diverse trends, the observed and projected patterns in these indicators provide valuable insights for policy effectiveness evaluation and offer a temporal context for interpreting social sustainability outcomes. Overall, these projected trends collectively suggest that while the V4 countries are making progress in specific areas like recycling and emissions reduction, significant challenges remain in consumption patterns, waste generation, and achieving higher circularity rates that could enhance the transition to a more self-sufficient circular economy by 2030.

Building on these temporal insights from Fig. 3, which traced the evolution and future projections of key circular economy indicators, it becomes evident that environmental trends alone cannot fully capture the region's sustainability trajectory. Indeed, the relationships between resource use, waste generation, and circular practices directly shape and are shaped by social outcomes such as healthcare investment, welfare protection, and income equity. Therefore, to achieve a truly integrated view of sustainability progress within the Visegrád countries, it is essential to examine how social sustainability indicators have developed alongside environmental metrics and how they are projected to evolve. The following section extends this systems perspective by exploring the temporal dynamics and ARIMA-based forecasts of social sustainability indicators, as visualized in Fig. 4.

Extending the time series approach to the social domain, Fig. 4 presents the historical and projected trajectories of social sustainability indicators, modeled using the ARIMA framework outlined in Eq. (4). The trend data has been split into blue (2014–2020), yellow (2021–2023), and red (2024–2030) to denote different time periods.

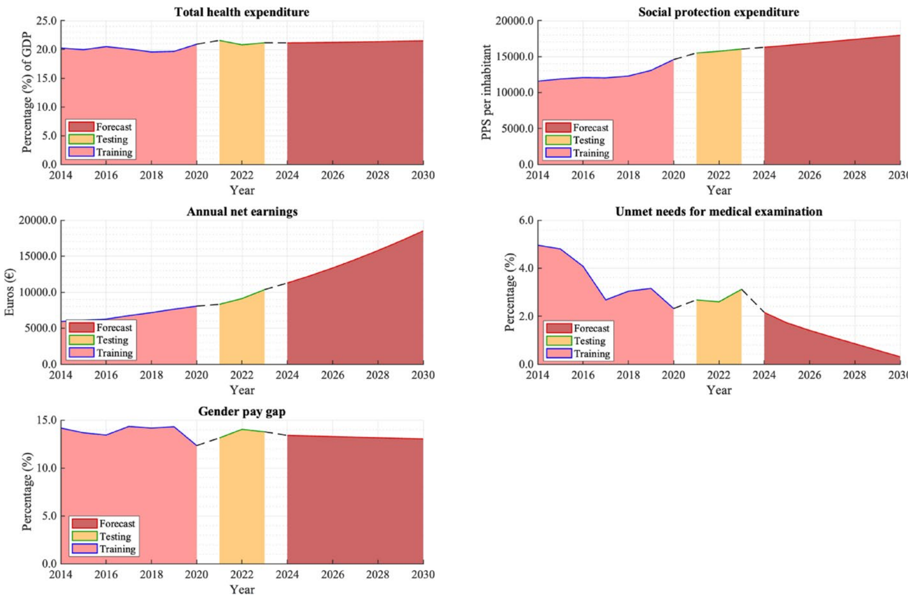

Fig. 4 Temporal dynamics and future projections of social sustainability indicators for Visegrád countries (2014–2030): historical patterns and forecast models

Beginning with healthcare investment patterns, the total health expenditure indicator shows remarkable stability throughout the observed period. Specifically, this indicator exhibits consistent performance, maintaining approximately 20% of GDP from 2014 to 2020. During the subsequent testing period, the data confirms this stability with minimal fluctuation. Looking toward the future, the forecast indicates a minor upward shift, projecting a level of approximately 21% by 2030. This sustained high level of health expenditure reflects the V4 countries' consistent prioritization of healthcare systems, though the minimal projected growth suggests limited expansion of healthcare spending relative to economic growth.

Turning to social welfare provisions, social protection expenditure, measured in Purchasing Power Standards (PPS) per inhabitant, demonstrates a steady upward trajectory. Initially starting at approximately 12,000 PPS in 2014, it increases progressively to around 14,000 PPS by 2020. Continuing this positive trend, the testing period shows sustained growth to approximately 16,000 PPS. Most encouragingly, the forecast projects further substantial increases, reaching approximately 18,000–19,000 PPS by 2030. Overall, this represents a significant growth of approximately 50–60% compared to 2014 figures. This trend indicates expanding social safety nets across the V4 region, thereby potentially enhancing resilience against economic shocks and improving quality of life for vulnerable populations.

In terms of economic prosperity, annual net earnings, expressed in Euros (€), displays substantial growth among the indicators. Starting from approximately €6000 in 2014, earnings increase steadily to about €8000 by 2020. During the testing period, accelerated growth is evident, reaching approximately €11,000 by 2023. Projecting forward, the forecast anticipates continued strong growth, with earnings potentially reaching €18,000 by 2030. Remarkably, this forecast represents a substantial increase of approximately 260% from the earnings observed in 2014. This trajectory suggests significant economic prosperity and improved living standards for V4 citizens, although questions of income distribution and inequality remain unaddressed in this aggregate measure.

Examining healthcare accessibility, the unmet needs for medical examination indicator, expressed as a percentage, shows substantial improvement over time. Beginning at approximately 5% in 2014, the figure demonstrates a steady decline through the training period to around 3% by 2020. Continuing this positive trajectory, the testing period shows further improvement to approximately 2.5%. Most promising, the forecast projects a continued decline to approximately 0.5% by 2030. This represents a dramatic improvement in healthcare accessibility, suggesting V4 countries are on track to nearly eliminate barriers to medical care, thus representing a significant advancement in health equity.

However, addressing a persistent challenge, the gender pay gap, measured as a percentage difference between male and female earnings, presents a more stable but concerning picture. Throughout the training period, this indicator remains relatively consistent at approximately 13–14%. During the testing phase, the gender pay gap shows minimal variation, maintaining around 14%. Unfortunately, the forecast projects only modest improvement, decreasing to approximately 13% by 2030. While this represents progress, the rate of change is gradual, indicating that substantial gender equality improvements will require more targeted and intensive policy interventions.

Synthesizing these diverse social trends, the patterns depicted reveal both significant progress and persistent challenges in advancing social sustainability alongside circular economy initiatives. On the positive side, strong ARIMA(1,1,1) model performance during testing (model diagnostics in Supplementary Fig. 1 and Fig. 2) reveals projected substantial progress in economic prosperity, social protection, and healthcare access for the V4 countries. Conversely, gender equality remains a key challenge with limited forecast improvement, thereby indicating an uneven social sustainability path requiring targeted policy attention.

Building on these social sustainability insights, and considering the interconnections between the environmental trends explored in Fig. 3 and the social patterns revealed here, it becomes clear that the V4 region faces a complex sustainability landscape. To further facilitate a comprehensive understanding of these regional disparities and clustering patterns in circular economy and social sustainability across the Visegrád region, the following clustered heatmap (Fig. 5) is presented. This visualization facilitates a direct comparison of values across Visegrád regions, highlighting both magnitude and distributional characteristics of integrated performance.

To synthesize the multidimensional performance of each country, Fig. 5 displays a clustered heatmap of composite indices, constructed using min-max normalization (Eq. (1)), composite aggregation (Eq. (2)), and hierarchical clustering (Eq. (5)). The colour gradient transitions from light yellow (lowest values around 0.20) to deep green (highest values around 0.74), with each row representing a country observation point and the dendrogram on the left illustrating hierarchical clustering of similar performance patterns.

The hierarchical clustering clearly separates the observations into three main groups: a top-tier cluster dominated by Czechia's high-performing instances; a middle cluster mixing moderate performances from all four countries; and a bottom cluster predominantly composed of Hungarian observations.

Czechia emerges as the top performer among the Visegrád countries, consistently demonstrating high values across both dimensions. Specifically, Czechia shows excellent balanced performance with circular economy scores ranging from 0.57 to 0.74 paired

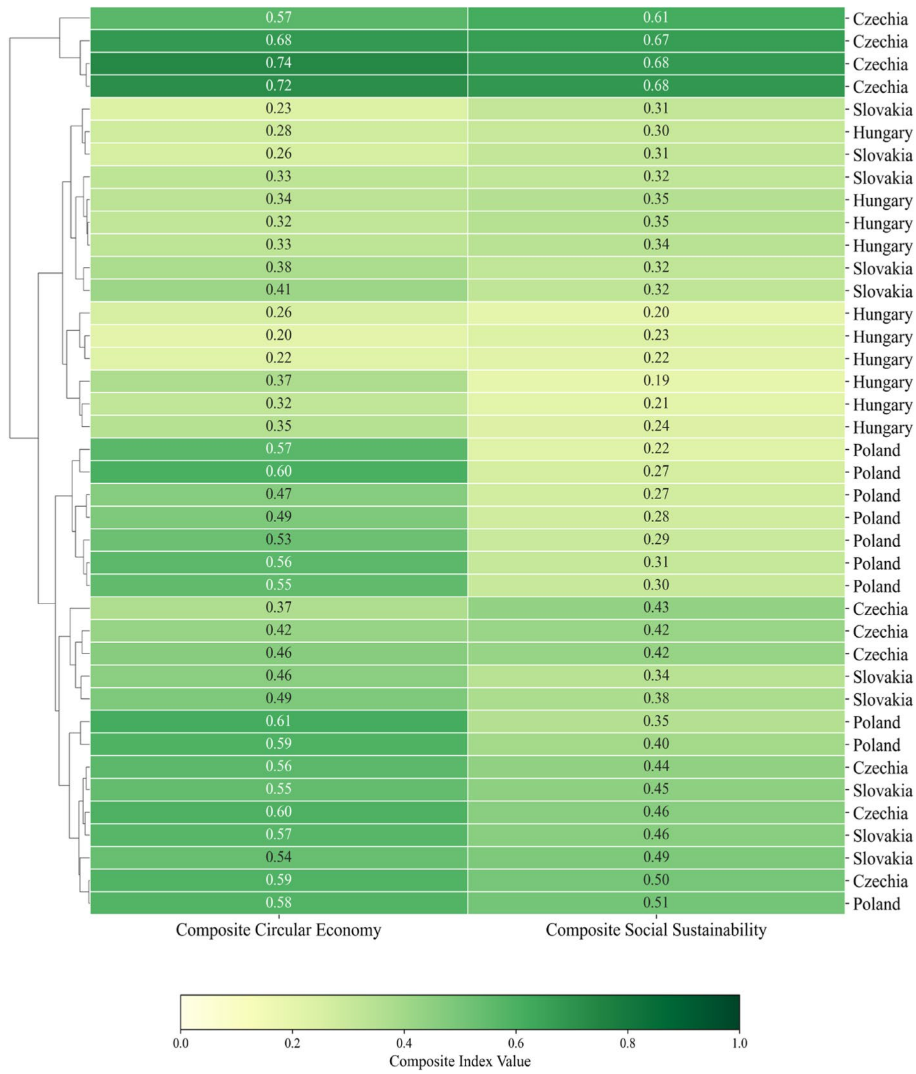

Fig. 5 Hierarchical clustering of integrated circular economy and social sustainability performance across Visegrád countries (2014–2023)

with social sustainability scores of 0.61–0.68. Four specific Czechian observations are particularly strong (0.57/0.61, 0.68/0.67, 0.74/0.68, and 0.72/0.68), indicating successful integration of environmental and social considerations. Even Czechia's lower-performing instances (0.37–0.46 for Circular Economy paired with 0.42–0.50 for Social Sustainability) maintain better balance than many observations from other countries in the region.

Poland exhibits a distinctive pattern characterized by stronger circular economy performance but comparatively weaker social sustainability outcomes. The country achieves circular economy scores between 0.47 and 0.61, while social sustainability scores remain relatively low (0.22–0.40), with only one observation reaching 0.51. This pattern is particularly evident in instances where Poland achieves circular economy scores above 0.55 while social sustainability remains below 0.35 (e.g., 0.57/0.22, 0.60/0.27, 0.56/0.31), suggesting that economic circularity does not automatically translate to social benefits in the Polish context.

Slovakia generally occupies the middle ground in regional performance. Its observations appear in both the top and middle clusters, with circular economy scores ranging from 0.23 to 0.57 and social sustainability scores between 0.31 and 0.49. Slovakia's strongest showing includes values of 0.54–0.57 for circular economy paired with 0.46–0.49 for social sustainability. While not reaching Czechia's highest levels, Slovakia maintains relatively balanced scores between the two dimensions across most instances.

Hungary consistently ranks as the lowest performer in the Visegrád region, with multiple observations showing very low scores in both indices. Hungary's scores range from 0.20 to 0.37 for circular economy and 0.19–0.35 for social sustainability. Particularly concerning are instances with extremely low values in both dimensions (0.20/0.23, 0.22/0.22, 0.26/0.20), representing the region's poorest integration of these sustainability aspects. Only Hungary's better performances (0.32–0.34 for circular economy paired with 0.34–0.35 for social sustainability) approach the mid-range values seen in other countries.

This clustering reveals significant regional disparities, with Czechia demonstrating that high performance in circular economy typically accompanies strength in social sustainability. Poland shows an intriguing pattern of prioritizing circular economy development without achieving proportional gains in social sustainability, suggesting potential policy trade-offs or implementation gaps. Hungary faces the greatest challenges in both dimensions, requiring comprehensive sustainability reforms to catch up with regional peers. This visualization brings together the study's key findings, illustrating regional disparities and integration patterns that are further discussed in the subsequent section.

5 Discussion

This research provides a novel contribution by revealing robust synergies between circular economy adoption and social welfare outcomes in the Visegrád region. Countries exhibiting more intensive material use and higher circularity tend to invest more in public health and social protection. For instance, the Circular Material Use Rate (CMUR) shows a statistically significant positive correlation with Total Health Expenditure ($r = 0.4225$, $p = 0.0066$) and Social Protection Expenditure ($r = 0.4068$, $p = 0.0092$), indicating that circularity is often embedded within broader systems of public investment and welfare provisioning. Similarly, Material Footprint (MF) correlates strongly with Social Protection Expenditure ($r = 0.6629$, $p < 0.0001$) and Annual Net Earnings ($r = 0.6236$, $p < 0.0001$), suggesting that resource-intensive economies are often those with greater fiscal capacity to support social stability. These patterns support the study's central hypothesis that gains in resource efficiency and waste reduction can go hand-in-hand with social investment, reinforcing a "win-win" scenario in which circular policies not only reduce environmental burdens but also deliver tangible social dividends.

Critical reflection on these findings reveals significant political and institutional dimensions that warrant deeper analysis. The stark performance disparities between Czechia (CE index: 0.74, SS index: 0.68) and Hungary (CE index: 0.20, SS index: 0.19) cannot be attributed solely to resource availability or economic capacity, but rather reflect fundamental differences in governance structures, policy coherence, and administrative effectiveness. Hungary's persistent underperformance across both domains suggests systemic institutional weaknesses that impede integrated sustainability transitions, including fragmented ministerial coordination, limited stakeholder engagement, and insufficient absorption of EU cohesion funds. Conversely, Czechia's success appears rooted in more coherent policy frameworks that effectively synchronize environmental and social objectives through inter-ministerial coordination and strategic use of European structural funds. These patterns align with broader European evidence demonstrating that countries with fragmented governance structures struggle to capitalize on circular economy opportunities while simultaneously addressing social inequities. The political implications extend beyond national borders, as divergent sustainability trajectories within the V4 group may create tensions in regional cooperation and complicate coordinated responses to EU sustainability mandates. This geographical heterogeneity underscores the critical role of territorial factors, including varying governance capacities, regional economic structures, and local institutional frameworks in shaping circular economy and social sustainability outcomes. The stark performance differences between countries likely reflect not only national policy frameworks but also subnational territorial dynamics that influence implementation effectiveness and local adaptation of sustainability initiatives.

The empirical findings both complement and challenge existing literature in important ways. While the results align with Oliveira et al. [62] regarding the necessity of multi-dimensional approaches, this regional focus reveals more pronounced disparities than their broader European analysis suggested. Specifically, the clustering analysis demonstrates that Czechia consistently outperforms regional peers across both dimensions, whereas Oliveira et al. found more gradual convergence patterns across EU member states [62]. Similarly, these findings extend the work of Georgescu et al. [63]. Their research documented positive correlations between technological development and circularity at the European level [63]. However, the country specific forecasts reveal that technological advancement alone does not automatically translate into social benefits without deliberate policy coordination. This is evidenced by Poland's relatively strong CE performance (0.47–0.61) coupled with weak social sustainability scores (0.22–0.40). This diverges from Georgescu et al.'s more optimistic assessment of technology-driven sustainability transitions. Furthermore, the temporal analysis provides empirical support for Padilla-Rivera et al. (2020)'s theoretical concerns about the underexplored social dimensions of circular economy transitions [15]. The forecast of persistent gender pay gaps (Poland: 7.80% by 2030, CI: 0.81–14.79%) directly confirms their warning that circular transitions risk perpetuating existing inequalities without targeted interventions. Most significantly, these findings challenge Wang et al. (2025)'s suggestion that policy fragmentation primarily affects implementation efficiency [18]. The evidence indicates that fragmented governance fundamentally undermines the synergistic potential between environmental and social outcomes, as demonstrated by Hungary's consistently low performance across both domains.

Several plausible mechanisms explain these linkages. Circular economy strategies-such as recycling, repair, remanufacturing, and localized production-tend to create labor-intensive industries that not only absorb workers, including those from vulnerable populations, but also generate taxable income to fund social programs. Reports from the International Labour Organization (ILO) underscore that recycling and repair sectors offer large-scale employment potential while upgrading informal or precarious jobs into more stable roles [14]. This is reflected in the study's empirical data, where the average number of persons employed in CE sectors in the V4 region stood at 181,396, though with high variability (SD = 136,264), pointing to uneven sectoral development across countries. In the Visegrád context, more resource-intensive countries may also be those with higher GDP per capita, and thus greater fiscal space for welfare investment. Moreover, circular practices reduce exposure to environmental externalities-such as air pollution and landfill overflow-that disproportionately affect lower-income populations, indirectly improving health outcomes and reducing long-term public health burdens.

The interdependence between environmental and social systems observed here aligns with ecological modernization theory and integrative sustainability models, which argue that environmental transitions-when aligned with inclusive governance-can catalyze co-benefits for society. Our time-series data and ARIMA-based projections reinforce this view. For example, Czechia's social protection expenditure is forecast to increase to €6,342.45 per inhabitant by 2030 (95% CI: €4235.11–€8449.79), while Poland's Annual Net Earnings are projected to reach €18,000 by 2030, representing a 260% increase from 2014 levels (see Supplementary Table 1 for confidence intervals and test statistics). This result suggesting continued upward trajectories in economic well-being and state capacity. These results are in line with the findings of Georgescu, I. et al. [63], who, using a panel approach, demonstrated that technological development and circularity are linked to economic growth in Europe, but also cautioned that without supportive social and regulatory frameworks, gains in circularity might not translate into broader social benefits [63].

However, these positive linkages are neither automatic nor universal. Some expected relationships were weak or statistically insignificant. A modest negative correlation was observed between CMUR and the Gender Pay Gap ($r = -0.2839$, $p = 0.0758$), suggesting that higher circularity may contribute to gender equity, but the effect is not strong. Although green transitions are often framed as inclusive, empirical data reveals that the average gender pay gap in the V4 region remains significant at 13–14% and is projected to persist at 13% by 2030, indicating limited progress. These figures mirror broader findings that technical innovations or environmental reforms, in the absence of targeted interventions, often fail to address structural inequalities. Padilla-Rivera et al. (2020) similarly note that the social dimensions of the circular economy remain underexplored and that more research is needed to understand how circular transitions impact equity and inclusion [15]. Women remain underrepresented in many green sectors, and without gender-sensitive planning, circular transitions risk replicating traditional hierarchies rather than dismantling them. As emphasized by the European Centre for Development Policy Management (ECDPM) and ILO, incorporating care economy linkages, gender training, and inclusive employment pathways into CE initiatives is crucial [64, 65].

The geographical disparities in circular-social performance further reinforce the importance of institutional context. Czechia consistently outperforms the other V4 countries across both sustainability dimensions, with CE index values as high as 0.74 and social sustainability scores up to 0.68. In contrast, Hungary demonstrates systemic underperformance in both domains, with CE scores ranging between 0.20 and 0.37 and social sustainability values from 0.19 to 0.35. This divergence suggests that macro-level policy integration, regulatory coherence, and administrative capacity significantly mediate CE and social sustainability outcomes. National strategies and regional development funds must therefore be attuned to these contextual realities. These comparative findings are echoed by Wang, Y. et al. (2025), who documented those countries with fragmented governance and weak policy integration struggle to realize the full benefits of circular economy transitions [18].

This study findings also illuminate critical temporal dynamics. The recycling rate of municipal waste shows a strong positive trajectory, rising from 22% in 2014 to a projected 37–40% by 2030. However, this is contrasted by concerning trends in material consumption. Municipal waste generation per capita is forecast to rise from 1000 kg in 2014 to 1500 kg by 2030, and material import dependency is expected to remain stable at approximately 39%, underscoring persistent challenges in decoupling growth from resource extraction and waste. These tensions highlight the need for upstream interventions focused on dematerialization, product redesign, and consumption reduction, alongside downstream solutions like recycling.

In light of these findings, the broader implications for theory and policy are significant. The observed positive associations between CE and social metrics validate calls for integrated sustainability frameworks that bridge environmental efficiency with social equity. Theoretically, this supports the growing consensus that the circular economy must be embedded within social-justice-oriented transitions, not merely technological substitution. For policymakers, the message is clear: circular economy measures must be designed in coordination with inclusive social policies. EU strategies-such as the Circular Economy Action Plan and the European Pillar of Social Rights-must be more deliberately synchronized [56]. For example, cohesion funds or just transition mechanisms could prioritize CE initiatives that demonstrably create local jobs, improve public health, and empower marginalized communities [55, 66].

Conversely, neglecting the social dimension risks undermining the legitimacy and effectiveness of CE reforms. The transition to a circular economy must therefore be governed not just by metrics of material reuse or emissions reductions but by social indicators including employment quality, health access, and gender equity. As the ILO and ECDPM have stressed, embedding equity considerations into green industrial strategies is not just ethically necessary but functionally advantageous, ensuring broader support and resilience.

Overall, this study confirms that circular economy advancement in the Visegrád region holds substantial promise for enhancing social sustainability. However, this potential will be fully realized only through deliberate, inclusive, and integrative strategies. Environmental reforms that reduce material throughput and waste must be paired with proactive social investments-healthcare, welfare, inclusive employment-to ensure that the benefits of sustainability transitions are equitably distributed. A just transition framework is thus indispensable. Policymakers, stakeholders, and researchers must work collaboratively to embed social criteria into circular economy policies, ensuring that Europe's shift toward sustainability is truly transformative, not only for the planet but for all of its people.

6 Conclusion

This study offers a comprehensive, cross-domain examination of the historical trajectories and projected futures of circular economy and social sustainability indicators in the Visegrád region. Utilizing empirical trends, correlation analysis, and time series forecasting, this study provides robust evidence that higher circular material use rates and more expansive recycling systems, as indicators of improved circular economy performance, are positively associated with greater public health investments, increased social protection spending, and enhanced income equity. These findings substantiate the premise that environmental and social objectives can be mutually reinforcing, especially when embedded within coherent policy frameworks and supported by institutional capacity.

Nonetheless, several limitations require caution in interpreting these results. First, reliance on aggregated national-level data likely conceals subnational heterogeneity and localized variation, limiting insight into disparities between regions, urban and rural territories, or distinct demographic groups. Second, while ARIMA models provide structured forecasting, projections are subject to uncertainty given the limited historical time series and the presence of non-stationary or volatile indicators, which may affect model robustness and confidence intervals. Third, the analytic focus on correlation rather than causal inference means that observed associations do not establish directionality or mechanisms; future studies employing longitudinal, panel, or qualitative designs are needed to elucidate underlying causal pathways and contextual drivers.

Based on these findings, several critical policy recommendations emerge for the Visegrád region and broader European context. First, EU cohesion and Just Transition Fund allocation should explicitly prioritize integrated CE-SS projects that demonstrate measurable cross-domain benefits, particularly in lagging regions like Hungary. Second, national governments should establish inter-ministerial sustainability coordination mechanisms, following Czechia's successful model of policy integration. Third, gender-responsive green job creation programs are urgently needed, incorporating care economy linkages and flexible employment arrangements as recommended by the ILO and ECDPM. Fourth, subnational monitoring systems should be developed to capture regional disparities masked by national-level aggregation, enabling more targeted interventions.

Future research should address several critical gaps identified by this analysis, with particular emphasis on territorial and subnational dimensions. First, subnational analyses should be prioritized to capture territorial disparities masked by national aggregates, examining how regional governance structures, local economic specialization, and territorial policy integration affect CE-SS linkages to support more effective, place-based sustainability strategies. Second, longitudinal case studies examining successful policy integration mechanisms in leading countries like Czechia could provide actionable insights for lagging regions, while comparative territorial case studies could illuminate how place-based factors mediate the relationship between circular economy policies and social sustainability outcomes. Third, causal inference approaches exploiting policy variation or natural experiments are needed to move beyond correlational evidence and establish definitive causal pathways between circular economy measures and social outcomes across different territorial contexts. Fourth, qualitative research exploring how different demographic groups and territorial communities experience circular economy transitions could illuminate the distributional consequences obscured by aggregate indicators. Finally, comparative analysis extending beyond the V4 context to other post-transition economies could test the generalizability of these findings regarding both institutional and territorial determinants of integrated sustainability performance. These research directions are essential for developing evidence-based, territorially sensitive strategies that ensure Europe's circular economy transition delivers on its promise of environmental protection while advancing social justice and equity across diverse regional and local contexts.

Ultimately, this research highlights the critical importance of aligning environmental innovation with social equity. The Visegrád countries, despite disparities in performance, demonstrate that circular economy policies, when thoughtfully integrated with social policy, can drive not only material efficiency and emissions reductions but also strengthen welfare systems, reduce unmet health needs, and support progress toward income and gender equity.

As the European Union advances its Green Deal and Circular Economy Action Plan, these findings underscore the necessity of embedding social sustainability at the core of circular transitions. The full promise of a just and sustainable European future can be realized only through a deliberately inclusive, evidence-based strategy.

Abbreviations

CE	Circular economy
SS	Social sustainability
EU	European union
V4	Visegrád region (Czechia, Hungary, Poland, Slovakia)
ARIMA	Autoregressive integrated moving average
CMUR	Circular material use rate
MF	Material footprint
PPS	Purchasing power standard
GDP	Gross domestic product
ACF	Autocorrelation function
PACF	Partial autocorrelation function
SD	Standard deviation
IQR	Interquartile range
ADF	Augmented Dickey-Fuller (test)
AIC	Akaike information criterion
JB	Jarque-Bera (test)
CI	Confidence interval
Q	Ljung-Box Q statistic
CO_2	Carbon dioxide
EMT	Ecological modernization theory
ILO	International labour organization
ECDPM	European centre for development policy management

Supplementary Information

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Supplementary Material 1

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Data availability
All data were sourced from the Eurostat database (https://ec.europa.eu/eurostat/web/main/data/database), a publicly accessible resource. This study utilized harmonized and comparable statistics for the Visegrád countries (Czechia, Hungary, Poland, and Slovakia) from 2014 to 2023. No proprietary or confidential data were used. Specific datasets and variables are fully documented in the Methodology section and Table 1. Processed data and analytical code are available from the corresponding author upon request to ensure full transparency.

Declarations

Ethics approval
Not applicable.

Consent to participate
Not applicable.

Consent to publish
Not applicable.

Competing interests
The authors declare no competing interests.

Clinical trial registration
Not applicable—this study does not report results of a clinical trial.

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