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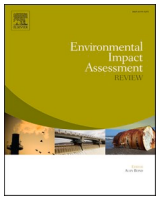

Existing gaps in understanding Sustainable Development Goals interactions: Insights from a systematic review

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ABSTRACT

Most countries remain off track to fulfil the 2030 Agenda's 17 Sustainable Development Goals (SDGs) and 169 targets. One key challenge to achieving the 2030 Agenda lies in trade-offs arising from cherry-picking goals or targets at the expense of others. Overlooking these SDG interactions, i.e., synergies and trade-offs, risks creating conflicting policies that undermine the interconnected nature of sustainable development. Hence, there is a need to comprehensively understand how the interactions are being addressed in the growing body of literature. This study provides a systematic review of 272 articles selected from an initial search of 1818. The review reveals that interactions between targets within individual goals and occurring across different geographic boundaries are understudied. The fragmented representation of geographic scales in existing studies highlights another gap, emphasizing the need to understand local SDG interactions. Further, SDG interaction studies infrequently focus on low-income countries, revealing a geographic bias. Notably, an imbalance persists in SDG coverage, with SDGs requiring complex social, institutional, or political engagement (e.g., SDGs 5, 10, 16, and 17) remaining underrepresented in the literature. Most interaction studies focus on goal level rather than more granular target or indicator level analysis. By observing the trends and co-occurrence of methods used for interaction analysis, this study highlights the dominance of qualitative text-based and stakeholder-inclusive methods and a need to develop new approaches to analyze the interactions underlying causal mechanisms. By identifying key gaps and trends, this review can be leveraged to advance the research landscape, guiding the prioritization of SDGs.

1. Introduction

With only 17 % of targets on track for the '2030 Agenda for Sustainable Development', countries are far from fulfilling their historic commitment to a sustainable future (Sachs et al., 2024). At the inception of the agenda, the 17 Sustainable Development Goals (SDGs) and their 169 targets were marked as indivisible and part of an interconnected system (Pradhan, 2019). Within this system, progress on one goal or target can have either a positive (synergistic) or negative (trade-off) effect on others (Nilsson et al., 2016). Beyond the internal trade-offs, externalities in the form of global impediments, such as the COVID-19 pandemic, geopolitical tensions, natural disasters, and financial crises, also hinder SDGs' progress (UN, 2024). Furthermore, the coordinated action towards the ambitious vision of the SDGs faces systemic challenges, including insufficient funding (Klees, 2024; Filho et al., 2019), limited political impact due to negligible policy or institutional reforms (Biermann et al., 2022), weak accountability at national and global scales, and selective implementation of goals, i.e., cherry-picking vs. strategic prioritization (Forestier and Kim, 2020). Failing to achieve these goals will undermine socioeconomic stability and exacerbate environmental challenges, affecting the lives of billions of people worldwide (Pradhan, 2023). Thus, in the 2030 Agenda's final five years, understanding these internal and external interactions is crucial for accelerating progress.

Understanding the complex interactions among the SDGs enables policymakers to anticipate trade-offs and design more optimal strategies for sustainable development (Nilsson et al., 2018). Effectively leveraging insights on synergies and trade-offs can further accelerate progress towards the 2030 Agenda (Pradhan et al., 2017). A thorough examination of the expanding literature on SDG interactions over the past decade is necessary to support such efforts. As of early 2019, 70 studies on SDG interactions had been published and reviewed (Bennich

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et al., 2020). While subsequent SDG research has expanded exponentially (Yumnam et al., 2024), a comprehensive synthesis that holistically examines all studies on SDG interactions across methods, scales, and contexts has yet to be conducted.

Some studies reviewed tools and methodologies used for analyzing SDG interactions, highlighting gaps in their practical applicability for policymakers, though without conducting a systematic review of the broader literature (Assubayeva and Marco, 2024; Di Lucia et al., 2022). Others have undertaken systematic reviews but focused on specific aspects of interactions, such as network analyses (Issa et al., 2024). As many studies apply multi-method designs to assess interactions, these co-occurrences and how their combinations have evolved over time remain underexplored (Bennich et al., 2023). While an understanding of SDG interactions can enhance policy coherence (Breuer et al., 2019), their interpretations vary widely depending on the geographic and socio-economic contexts, data types used, and the SDG entities, i.e., whether goals, targets, or indicators are being analyzed (Warchold et al., 2022). More recently, recurring global patterns of synergies and trade-offs were identified (Bennich et al., 2023), yet this work excluded studies focused on specific goals or regional contexts, limiting its scope. Thus, given the recent surge in SDG research (Yeh et al., 2022), a systematic review of tools, methods, and their co-occurrence patterns is both timely and necessary to inform the development of more robust analytical frameworks to assess interactions.

To fulfil this need, along with systematically quantifying and deepening the understanding of the previously noted gaps, we conducted a screening of 1,818 initial records on SDG interactions, resulting in 272 relevant articles published between 2015 and 2024, guided by three research questions. First, we addressed the question of what types of SDG interactions are studied at different geographical scales. Here, the types of SDG interactions refer to whether the interactions are being studied between the goals, within the goal (between targets), or between the SDG framework and an external entity (e.g., COVID and climate mitigation measures). We also considered research that addresses SDG interactions occurring across geographical boundaries, where progress in a goal or target in one region affects progress in another. Second, we assessed which SDG entities are analyzed, at what level of granularity, and which goals or regions are over- or underrepresented in the literature. Third, we addressed the question of which methods and databases have been used to analyze SDG interactions, identifying patterns of methodological co-occurrence, complementarity, and gaps in diversity. Through this analysis, our review provides the most comprehensive

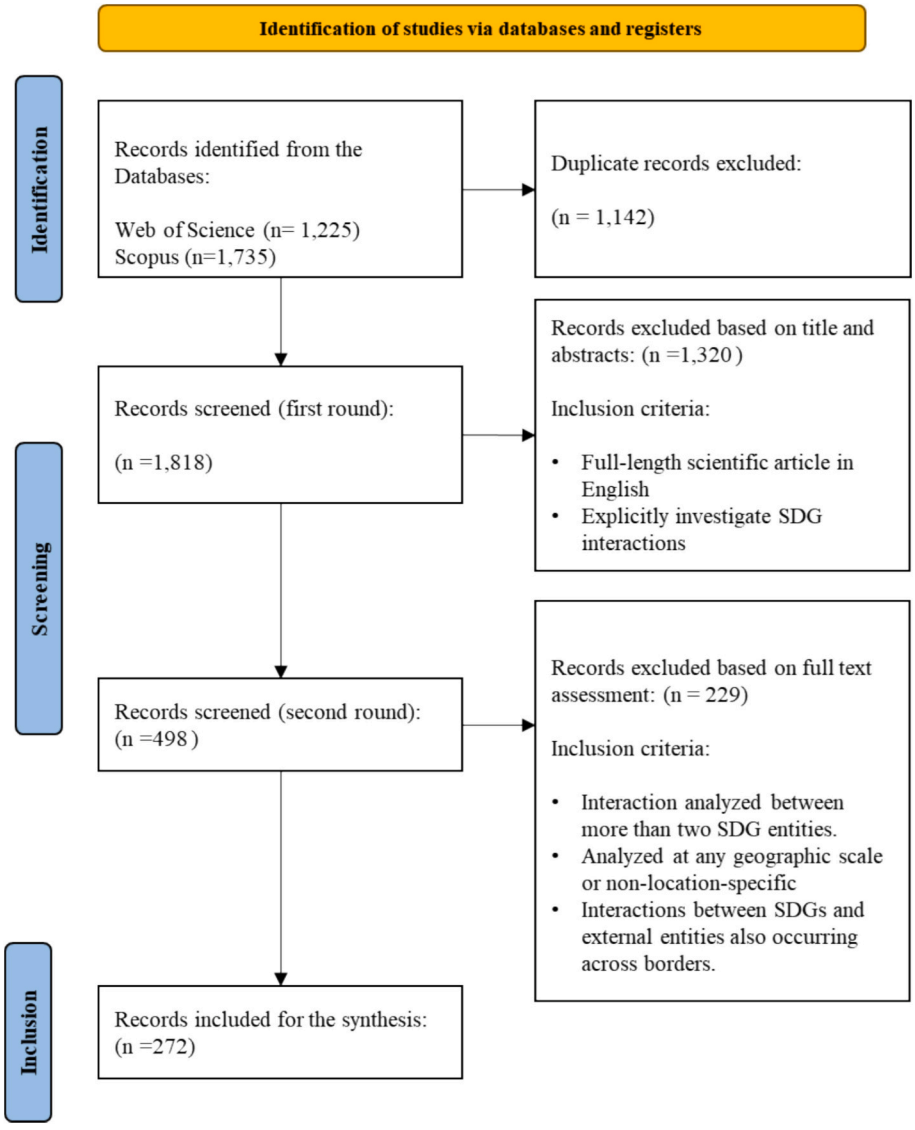

Fig. 1. An overview of the selection process for articles on SDG interactions by using the PRISMA method. The literature sample was finalized through stages of identification, two-fold screening, and the inclusion of relevant studies from Scopus and Web of Science databases. "n" refers to the number of records or articles.

mapping of SDG interaction studies to date, offering robust evidence that validates and refines prior observations in the literature, guiding the final years of the SDG until 2030.

2. Methodology

We reviewed the literature on SDG interactions using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework (Fig. 1), ensuring a systematic, transparent, and reproducible process for identifying, screening, and synthesizing literature (Page et al., 2021). Our review followed the steps: i) screening relevant articles based on established inclusion and exclusion criteria, ii) extracting information from designated data points, and iii) synthesizing key understandings.

2.1. Literature review process

We conducted the literature search across two prominent databases, Scopus and Web of Science, selected for their extensive coverage of peer-reviewed articles. The search syntax was structured to retrieve studies explicitly addressing SDG interactions. Primary keywords thus included "Sustainable Development Goals" and "interactions," along with closely related terms and synonyms. Here is the keyword search we applied for Scopus: *TITLE-ABS-KEY((("Sustainable Development Goal*" OR "SDG*" OR (2030 W/0 Agenda)) W/10 (synerg* OR "trade-off*" OR tradeoff* OR interdependenc* OR interlink* OR "inter-link*" OR interact* OR inter-connect* OR "inter-connect*" OR indivisibl* or spillover* OR conflict* OR cobenefit* OR "co-benefit*"))*.

We used the W/10 function to ensure words are used in specific combinations to limit the articles explicitly relevant to SDG interactions. A similar keyword strategy was employed for Web of Science, adapted to its syntax. Our review focused exclusively on peer-reviewed, full-length articles published from 2015 through May 2024, with 2015 selected as the starting point due to the adoption of the SDGs that year. The keyword search initially yielded 2,960 articles: 1,426 from Web of Science and 1,534 from Scopus. After removing duplicates, 1,818 articles remained. An initial screening based on title, abstract, and keywords identified 498 relevant articles written in English.

For the second round of screening, we manually reviewed the full text of each article. We included the articles that were freely accessible or obtained upon request from the authors. The screening applied the following inclusion criteria:

1) *SDG interactions:* The study examines interactions between more than two SDG entities, i.e., goals, targets, or indicators.
2) *Focused investigation:* The study explicitly investigates interactions, rather than merely mentioning them alongside the main analysis.
3) *Geographic scale:* Interactions are analyzed at any scale, from local to global, including non-location-specific and across geographic boundaries.
4) *SDG framework and external entities:* The article examines interactions between the SDG framework and external entities (e.g., policies, objectives, and phenomena) involving more than one goal, target, or indicator.

While grey literature and other sources such as book chapters, editorials, and commentaries can offer valuable insights, we excluded them to maintain a consistent scope limited to full-length peer-reviewed journal articles. We also removed literature reviews that did not analyze SDG interactions. This set of criteria narrowed the literature sample size to 272 articles.

2.2. Categorization of the articles

After selecting the relevant articles based on the predefined criteria, we categorized them using eight data extraction points for further analysis (Table 1). This categorization helps identify trends in SDG interaction research in a structured manner, enabling a more systematic understanding of how SDG interactions have been studied and answering our research questions.

Four types of SDG interactions were analyzed in the literature. Inter-goal dynamics, i.e., interactions within a single SDG, are classified as intralinkages. Whereas the interactions between two or more SDGs are classified as interlinkages. SDG entities also interact with agendas, policies, or phenomena external to the SDG framework. For example, global pandemics, country-level climate mitigation policies, and geopolitical conflicts, which are not inherently part of the SDGs but have the potential to impact them, are considered externalities. These types of interactions were noted as external-linkages (Bennich et al., 2023). Additionally, interactions also occur across geographic boundaries,

Table 1
Data extraction points to categorize the Sustainable Development Goal (SDG) interaction literature.

Data extraction point	Categories	Definition
Type of SDG interaction	Intralinkages	Interactions within a single SDG, such as target-to-target or indicator-to-indicator
	Interlinkages	Interactions between two or more SDGs, including their targets and indicators
	External-linkages	SDG entities interacting with external agendas, policies, or phenomena
	Transboundary-linkages	Interactions across geographic boundaries, where progress in one region influences another
Geographic scale	Sub-national	city, district, or state level
	national	e.g., the Netherlands, India, or Nepal
	Regional	e.g., the European Union or Asia
	Global	
	Non-location specific	Studies not focusing on a particular geographic area.
SDG entities	Goal level	SDG entities used in analyzing the interactions, which vary in granularity
	Target level	
	Indicator level	
SDGs covered	Goals covered in the literature	
Research method	Methods and tools used to analyze the interactions	i) statistical analysis: statistical methods (both descriptive and inferential), ii) text-based analysis: methods used for document analysis, iii) participatory approach: methods which engage stakeholders or experts, iv) network analysis: methods used from the network analysis family, v) spatial analysis: methods using geospatial data, vi) system/cause-effect analysis: methods applying system thinking, vii) other simulation based models: model simulation methods, viii) tools: predefined tools and frameworks, ix) other methods
Database used	Data sources utilized for analysis	
Externalities	External objectives, phenomena, or sectoral context applicable for external-linkages, e.g., circular economy, geopolitical crisis, or pandemics.	

where progress in SDGs in one region influences another. For example, exporting plastic or electronic waste to low-income countries may help high-income countries meet SDG 12 (Responsible consumption and production), but can undermine SDG 3 (Good health and well-being) in importing countries. Different transmission channels, such as international trade, human migration, wastewater flows, carbon emissions, ocean currents, etc., cause these spill-over effects (Xiao et al., 2023a, 2023b). These interactions between SDGs in separate regions, enabled by the transmission channels, are categorized as transboundary linkages.

The geographic scale was included as a category since SDG interactions are context-dependent, i.e., their nature varies across different spatial settings, and capturing it helps to contextualize how synergies and trade-offs manifest and are prioritized across scales ranging from local to global levels (Nilsson et al., 2018). We further listed the SDG entities used to analyze the interactions. These vary in granularity, ranging from broad goal-to-goal linkages to specific indicator-level relationships, thus reflecting the analytical depth of the literature.

The 'SDG covered' category identified which goals were represented in the literature and revealed common pairings of SDGs discussed together in the articles. For this, we first constructed a 17 × 17 SDG co-occurrence matrix, where each cell represented the number of articles that simultaneously addressed two goals. Principal Component Analysis (PCA) was applied to this matrix to reduce the high-dimensional information into two principal components that retained the most significant patterns of variation in SDG co-occurrence behavior (Hotelling, 1933). The first principal component (PC1) captures the dominant pattern of how SDGs tend to group or separate across studies. The second component (PC2) captures a secondary, independent variation in their relationships. Therewith, we identify clusters of SDGs frequently appearing together, along with those treated more independently, by projecting the SDGs onto a two-dimensional space based on these components. This dimensionality reduction indicates how SDGs are co-analyzed within the reviewed articles.

The 'research method' category outlined the methodologies and analytical tools employed to investigate SDG interactions. Existing classifications from previous reviewers were adopted to categorize the methods (e.g., Bennich et al., 2023; Di Lucia et al., 2022) into statistical analysis, text-based analysis, participatory approach, network analysis, spatial analysis, system/cause-effect analysis, other simulation-based models, tools, and other methods. We also tracked the co-occurrence of methods using the categorization of methods, helping to determine whether methodologies complement one another. A network diagram was built by extracting the methods used in each article and then identifying all method pairs that co-occurred. Pairs mentioned in at least four articles were retained, and their co-occurrence frequencies were used as edge weights. Nodes represent individual methods, with sizes proportional to their overall appearance in the articles. In addition, we traced the data sources used in each article, as the availability of data plays a significant role in evaluating and monitoring SDG progress and their interaction dynamics (Nilashi et al., 2023).

3. Results

3.1. Contextualization of Sustainable Development Goals

We identified a fragmented distribution in how SDG interaction types are prioritized and contextualized across geographic scales (Fig. 2). Goal-level interlinkages dominate, analyzed in 68 % of the articles, followed by external linkages in 33 % and intralinkages in 20 % of the studies (Fig. S1). Despite their growing importance in an interconnected world (Xiao et al., 2023a, 2023b; Xue et al., 2024), transboundary-linkages received marginal attention, being addressed in only 2 % of the articles. This selective focus also extends to the geographic context in which the research is conducted. Most SDG interaction studies are set at national (29 %) and global (26 %) scales, while comparatively fewer are conducted at regional (12 %) and sub-national (18 %) scales. Additionally, 11 % of the studies are non-location-specific, with analyses of synergies and trade-offs not tied to any particular location, region, or country (Fig. S2).

Multiple interaction types are often studied together, with intra-linkages frequently studied alongside interlinkage (45 articles). While interlinkage analysis dominates across all geographic scales (Fig. 2),

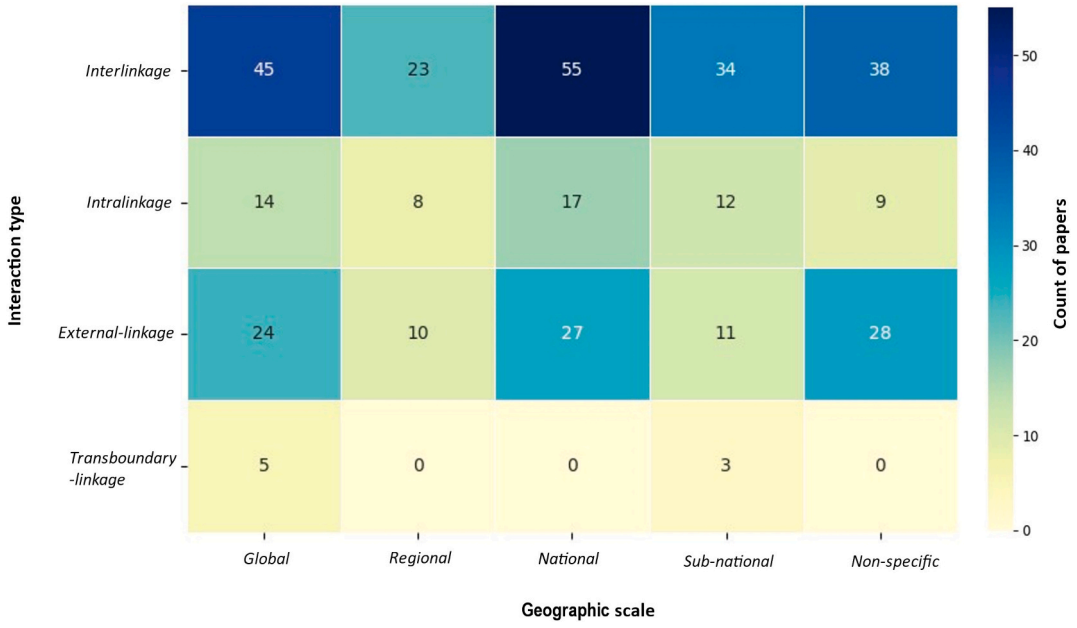

Fig. 2. Count of articles at different types of interactions versus the geographic scale at which they are analyzed. Interaction types and geographic scales represent distinct dimensions: conceptual and contextual, respectively. Their co-occurrence does not imply a direct analytical association. The heatmap shows patterns in how the academic community has chosen to study SDG interactions across geographic scales, identifying potential imbalances in the literature.

only two studies explicitly analyzed intralinkages (2 articles). Both focused on interactions between China's SDG 11 (Sustainable cities and communities) targets. These studies indicated that the strength and direction of synergies and trade-offs vary by scale, with differing interaction patterns observed at the basin level (Feng et al., 2023) versus the city level (Cheng et al., 2023). These findings underscore the contextual nature of local-level interactions and the need to analyze them separately. A comprehensive analysis of SDG interactions requires exploring internal consistency within goals (Gong et al., 2024; Lusseau and Mancini, 2019). Hence, more studies are needed to analyze intralinkages explicitly.

We observe a significant gap in studies examining transboundary linkages and their variation across geographic scales and governance contexts (Fig. 2). While still limited, recent SDG literature has begun to explore how sustainable development is influenced by various socio-economic and environmental spill-over effects. The transboundary-linkages enabled by complex human-caused transmission channels, such as international trade, foreign direct investment (FDI), tourism, or natural flows (e.g., rivers, air, and ocean currents), have varying impacts depending on the geographical scale of the linkages (Xiao, et al., 2023; Xue et al., 2024; Zhao et al., 2021). For example, on a global scale, human-caused flows exhibit stronger synergies between the SDGs of distant trade partners, whereas natural flows provide greater benefits to countries in proximity (Xiao et al., 2024). Economically or geographically linked nations can mutually enhance SDG progress (Xue et al., 2024), while sub-national analyses show that inter-city coordination and proximity further strengthen these synergies (Xiao et al., 2023a, 2023b). However, not all transboundary effects are positive or direct. Negative externalities such as biodiversity loss or pollution often affect regions uninvolved in the original flow (Zhao et al., 2021). FDI-driven development in the Global North has also produced significant negative spillovers, including environmental degradation and labor exploitation in less developed host countries, thereby questioning the rankings of the SDGs (Chen, 2024). The selected transmission channels and geographic proximity shape the direction and magnitude of transboundary interactions. Addressing them requires cross-border governance, spillover equity, and responsibility-sharing mechanisms in SDG planning.

Entities external to the SDG framework and their interactions have been mainly studied in a non-location-based context, receiving less attention at the sub-national and regional levels. The most common theme identified is climate action, noted in 11 articles. Across the relevant literature explicitly analyzing external-linkages, 27 distinct externalities were identified, spanning domains, for example, climate mitigation, sustainable practices, and COVID-19 (Data S1). These studies primarily assessed how the SDGs are affected by global strategies such as the Paris Agreement (Moreno et al., 2023) and other climate change or emission reduction measures at regional and national scales (Kluza et al., 2024; Sirigina and Nazir, 2022). The impact of COVID-19 was examined in 10 articles highlighting its role in hindering SDG progress through increased poverty, inequality, and disrupted health and education systems, especially in low-income countries (Yuan et al., 2023; Zhao et al., 2022). However, it also created synergies by accelerating digital innovation, environmental regeneration, and health system reforms (Martins et al., 2023). In recent years, geopolitical conflicts, which pose a global impediment to SDG progress, alongside Ecosystem services and the circular economy, have received attention as emerging externalities (Bin-Nashwan et al., 2024; Samekto et al., 2024).

Overall, synergies were reported more frequently than trade-offs, though their occurrence and the number of involved SDG entities varied considerably across identified externalities. Most studies assessed the direction of influence as unidirectional, i.e., from external entities towards SDG outcomes, suggesting limited attention to potential feedback effects. These findings highlight that while synergies dominate, their manifestations remain highly context-specific and not readily generalizable across externalities.

We observed that the least number of articles analyzed the SDG interactions at the regional scale (25 articles). Among these, the European Union (EU) is the most frequently studied region, appearing in 7 articles, followed by Africa (4 articles) and Asia (3 articles). In contrast, other

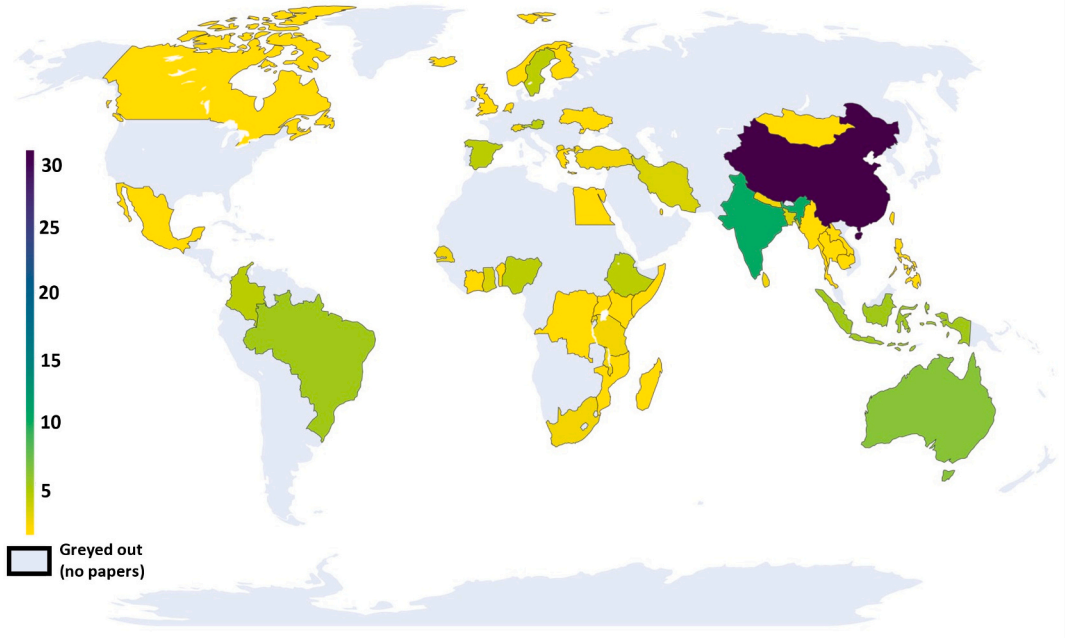

Fig. 3. Countries included in the SDG interaction analysis across the studies. The map does not indicate the origin of the research or the authors. The underlying studies examine interactions at the national, sub-national, or both levels. However, in this figure, the scale of analysis is not differentiated at the country level; for details related to the geographic scale, see Table S1.

regions such as Latin America, North America, and the Middle East are underrepresented. SDG interaction studies at national and sub-national levels are concentrated in specific regions, particularly in upper-middle-income and transitioning economies (Fig. 3). China has the highest number of studies (31), followed by India (10). Countries such as Australia, Brazil, and Indonesia appear moderately, with 5 to 6 articles each. Most other countries appear far less frequently, typically just once or twice, indicating that SDG research activity is clustered around a limited set of national contexts. Grouped by economic classification, upper-middle-income countries account for the most studies (48 articles across 8 countries), followed by lower-middle-income countries (42 across 18), high-income countries (31 across 16), and low-income countries (18 across 11). While upper-middle-income countries dominate in study volume, lower-income groups show broader geographic coverage, though with fewer studies per country, indicating a comparatively smaller contribution to the overall literature.

3.2. Entities of Sustainable Development Goals

We observed an imbalance in the representation of SDGs (Fig. 4). Goals related to basic human needs and environmental sustainability, such as SDGs 2 (Zero hunger; 80 articles), 6 (Clean water and sanitation; 81 articles), and 15 (Life on land; 79 articles), have received the highest attention. In contrast, SDGs 16 (Peace, justice, and strong institutions; 31 articles) and 17 (Partnerships for the goals; 17 articles), which require complex social, institutional, or political engagement, are least represented. SDGs 16 and 17 are often excluded because they are enabling goals focused on broad means of implementation, which are considered less tangible, difficult to assess, or not applicable at local scales (Ospina-Forero et al., 2022; van Zanten and van Tulder, 2021). Despite their critical role in inclusive development, SDGs 5 (Gender equality; 40 articles) and 10 (Reduced inequalities; 41 articles) are also relatively underrepresented. Many articles also exclude the marine-focused SDG 14 (Life below water; 39 articles), as the study areas considered for SDG interaction analysis didn't cover coastal regions (Kuc-Czarnecka et al., 2023; Wei et al., 2023).

The co-occurrence analysis of SDGs (Fig. 4) revealed a tendency for certain goals to cluster together, indicating that specific goal interactions are frequently examined. For instance, the well-established water-energy-food nexus (SDGs 2, 6, and 7) forms a prominent cluster (Cheng et al., 2023; Huang et al., 2024). Goals related to social development, such as SDGs 1 (No poverty), 3 (Good health and well-being), and 8 (Decent work and economic growth), are often analyzed together. Environmental goals, including SDGs 6, 13 (Climate action), and 15, also tend to co-occur in the studies. A similar pattern is observed between SDGs 11 and 12 (Responsible consumption and production). In contrast, SDGs 14, 16, and 17 appear more isolated, with limited co-occurrence with other goals. However, this can also result from their overall lesser representation in the studies. SDGs 5 and 10 also show fewer connections, appearing less frequently alongside the broader set of goals, yet still forming a cluster with SDG 4 (Quality education).

The SDG entities category revealed (Fig. S3) that while the analytical basis often starts at the indicator level (39 articles), more studies address interactions at the target level (74 articles) and the goal level (100 articles), reflecting a tendency to present findings at broader scales. Interactions involving external entities were also explored, with 58 articles linking external frameworks to SDGs, 33 to Targets, and only 11 to Indicators (Fig. S3). Some studies also aggregate indicator-level data to the target or goal level, balancing analytical simplicity while preserving the underlying multidimensionality of indicators (Hegre et al., 2020; Laumann et al., 2022). Lusseau and Mancini (2019) demonstrated that analysis of SDG interactions at the target level can result in insights different from those of the goal level. Different levels of granularity enable the examination of synergies and trade-offs at varying depths, with higher granularity offering more detailed insights. Goal-level analysis provides a broad overview of thematic linkages across the

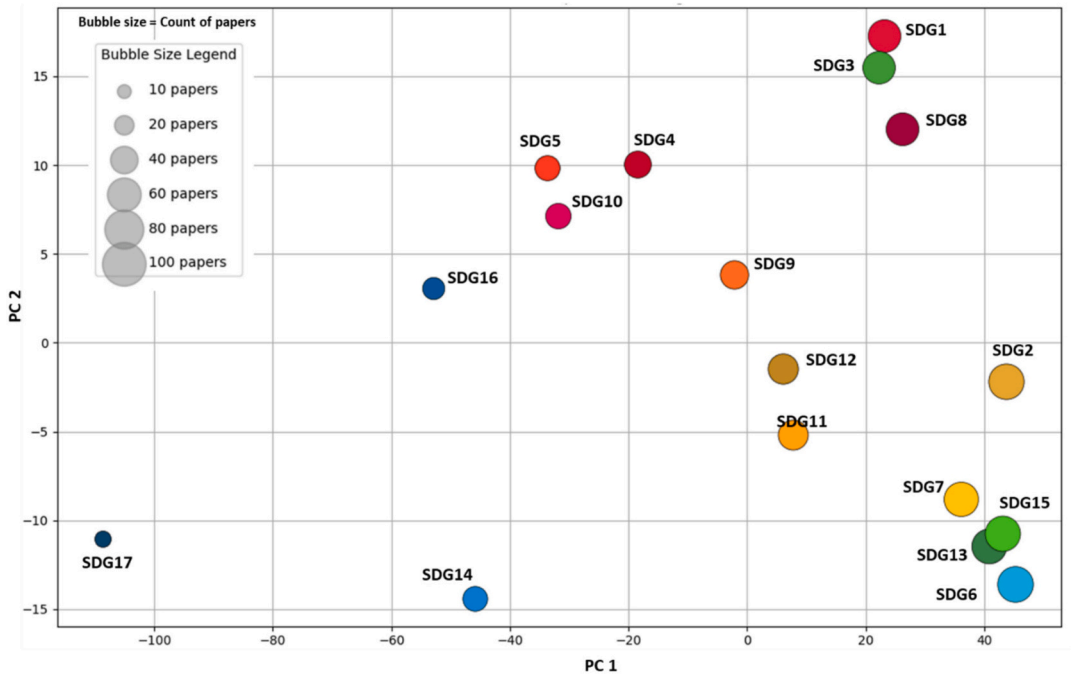

Fig. 4. Sustainable Development Goal (SDG) co-occurrence based on reviewed articles using Principal Component Analysis (PCA). Each bubble represents an SDG, and their spatial proximity reflects how frequently they are studied together. PC1 (x-axis) captures the primary pattern in how SDGs vary in their co-occurrence across studies, and PC2 (y-axis) captures the second most distinct co-occurrence pattern. The size of the bubbles indicates the number of articles in which each SDG is analyzed. Articles that studied all the SDGs (156) were excluded to avoid the inflation of the count, as their inclusion could mask the actual research priorities and dilute the visibility of SDGs that are more selectively addressed.

SDG framework, while indicator-level analysis captures finer details and reveals the specific mechanisms driving interactions. For instance, Gong et al. (2024) show that while SDG 17 appears as a central goal in the goal-level SDG interaction network, indicator-level analysis reveals that this results from weak but widespread links to indicators across various goals, a structural detail not discernible from goal-level analysis alone.

While considering the geographic scales (Fig. S6), we found that goal-level analyses dominate across all scales, with target-level studies accounting for a consistent secondary share that is slightly higher at the national and sub-national levels. Indicator-level analyses remain comparatively limited. This pattern indicates that SDG research overall is goal-oriented, with relatively modest uptake of fine-grained analysis at smaller spatial scales. Hence, differentiating analyses by scale and entity level allows a clearer representation of how SDG interactions are examined across thematic and spatial contexts.

3.3. Methods used for Sustainable Development Goal interactions

Various tools and methods have been used to analyze SDG interactions, which we grouped into nine distinct categories (See Table 2). Our investigation underscores a need for greater methodological diversity. Despite the use of 55 distinct methods, the field is dominated by qualitative text-based (26 %), participatory (23 %), and statistical approaches (20 %). In contrast, systems analysis (5 %), spatial analysis (3.5 %), and modeling (3 %) remain underutilized.

Many studies have used historical data to analyze SDG interactions (87 articles, Text S1). However, how synergies and trade-offs change through time is comparatively less analyzed (40 articles). Researchers have applied scenario analysis and simulation-based models to assess the temporal dynamics (Bandari et al., 2023; Wang et al., 2024). Integrated Assessment Models (IAMs) are also being used to analyze the dynamics of interactions in a few studies (Moreno et al., 2023; Moyer and Bohl, 2019). Although spatial analysis is now being used in the research, spatio-temporal dynamics remain understudied (11 articles). Some researchers have assessed transboundary-linkages using spatial econometric modeling (Xiao et al., 2024; Xue et al., 2024). Only a few studies have used Artificial Intelligence (AI) and, therewith, machine learning techniques to analyze SDG interactions (6 articles) (Asadikia et al., 2021; Sugiawan et al., 2023).

Our analysis reveals a clear evolution in methodological approaches over time, reflecting shifts in how SDG interactions are evaluated and monitored (Fig. 5). In the initial years post-inception of SDGs (2016–2018), the field was dominated by qualitative and participatory approaches, particularly text-based analysis and stakeholder engagement methods, reflecting an early focus on conceptual exploration and discourse analysis. The mid-years (2018–2020) showed methodological diversification with the introduction of network-based modeling and spatial analysis. In recent years (2021–2024), statistical and network-based methods have increased, while reliance on text-based and participatory methods has declined, indicating a field that is becoming more data-intensive. The consistently low use of systems analysis evident in only 21 articles suggests that more efforts are needed to integrate causal and systems-based frameworks.

Our analysis reveals the use of multi-method approaches in SDG interaction studies, where specific combinations of methods frequently co-occur (Fig. 6). Rather than relying on a single analytical technique, researchers integrate multiple methods to capture the complexity of SDG interactions. This co-occurrence reflects efforts to overcome the limitations of single-method approaches by leveraging their complementary strengths, capturing different types and scales of interactions, responding to data constraints, or cross-validating findings. Further, multi-method approaches can align with systems thinking, which requires analyzing the structure and dynamics of SDG interactions.

Synergies and trade-offs are not just mapped quantitatively but are contextualized and interpreted through normative scales and expert-based assessments. Nilsson's scale, in particular, provides a structured scoring framework ranging from strongly negative to strongly positive interactions (Nilsson et al., 2016), making it the most frequently used complementary tool (53 articles). Expert judgement is paired with both Nilsson's scale (27 articles) and literature review (27 articles), demonstrating efforts to formalize participatory assessments and ground them in evidence. Case studies on SDG interactions are primarily based on literature reviews (5 articles).

A broader examination of the co-occurrence network reveals frequent combinations between participatory, qualitative, and quantitative methods. Correlation analysis is often used with participatory methods such as Nilsson's scale, expert judgement (7 articles each), and surveys (5 articles). Cross Impact Matrix (CIM) commonly co-occurs with Nilsson's scale (14 articles) and expert judgement (13 articles), reflecting a methodological preference for integrating expert input into semi-quantitative frameworks. CIM also serves as an analytical foundation for network analysis (Huang et al., 2024; Pham-Truffert et al., 2020; Weitz et al., 2018). A less frequently used text-based approach, qualitative content analysis, co-occurred with network analysis (5 articles).

Less frequently used methods, such as system analysis, form smaller clusters within the co-occurrence network, appearing alongside qualitative methods to enrich analysis with narrative depth and institutional context. For example, fuzzy cognitive mapping and causal loop diagrams derive causal links from expert judgement (4 articles) and literature

Table 2
Methods and tools used for analyzing Sustainable Development Goal interactions. We list each analytical approach used in the relevant articles and categorize them accordingly.

Categorization	Analytical approach
Statistical analysis	Correlation analysis; Regression analysis; Proximity analysis; Principal component analysis; Hierarchical cluster analysis; Structural equation modeling; Granger causality analysis; Panel vector autoregressive model; Multifactor analysis; Advanced sustainability analysis; Simultaneous equation system; Coupling coordination model
Text-based analysis	Non-systematic review; Systematic review; Text mining; Qualitative content analysis; Natural language processing
Participatory approach	Expert judgement; Survey; Stakeholders' engagement; Delphi method
Network-based analysis	Network analysis; Social network analysis; Semantic network analysis
Spatial analysis	Remote sensing methods; LandSHIFT model; Co$tingNature model; WaterWord model; ANOVA model; Spatial econometric model
System/Cause-effect analysis	Fuzzy cognitive mapping; Interpretive structural modeling; System dynamic modeling (e.g., iSDG model, World3 model); DEMATEL model
Other simulation-based models	Computable general equilibrium modeling; Integrated Assessment Models (IAM); Econometric modeling; MARINA 2.0; Agent-Based Modeling; LEAP model; IMPACT model
Tools	Nilsson's scale; Causal loop diagram (tools, e.g., iModeler, STELLA); Cross impact matrix; DPSIR; SWOT; SDG Interlinkage tool
Others	Case study analysis; Grounded Theory; Metacoupling framework; Product space theory; Machine learning; Artificial neural network; Evidence-based mapping; Cost-benefit analysis; Welfare analysis

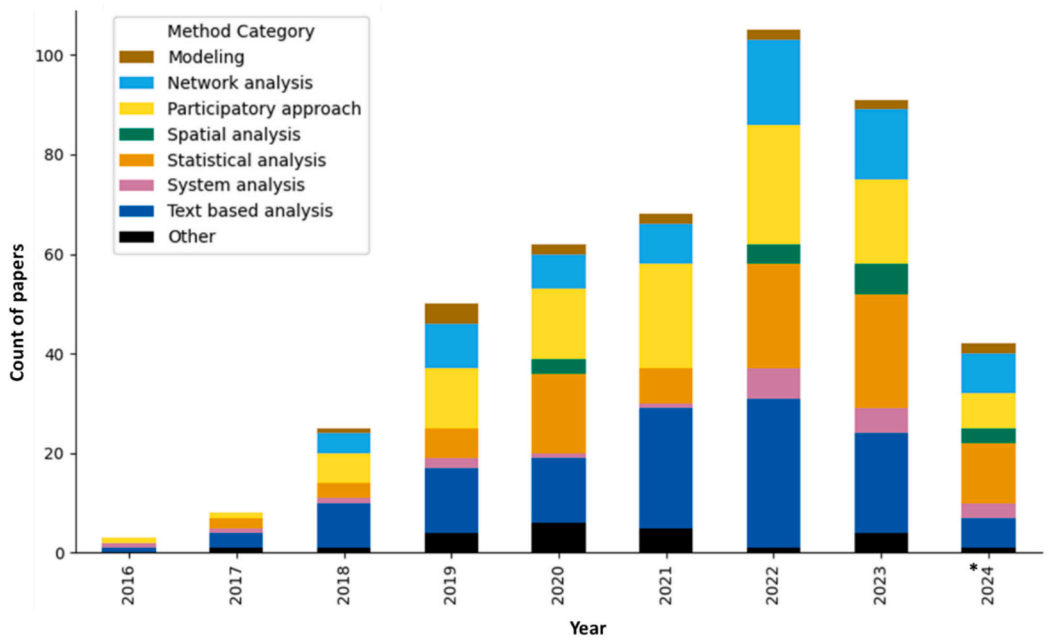

Fig. 5. Annual distribution of methodological categories used in SDG interaction studies from 2016 to May 2024. Each bar represents the total number of studies published in a year, categorized by method type. Notably, participatory, statistical, and text-based methods have grown significantly since 2018, while newer contributions from spatial and system analysis methods have emerged more prominently in recent years. The figure reflects a diversification in methodological approaches in SDG research.

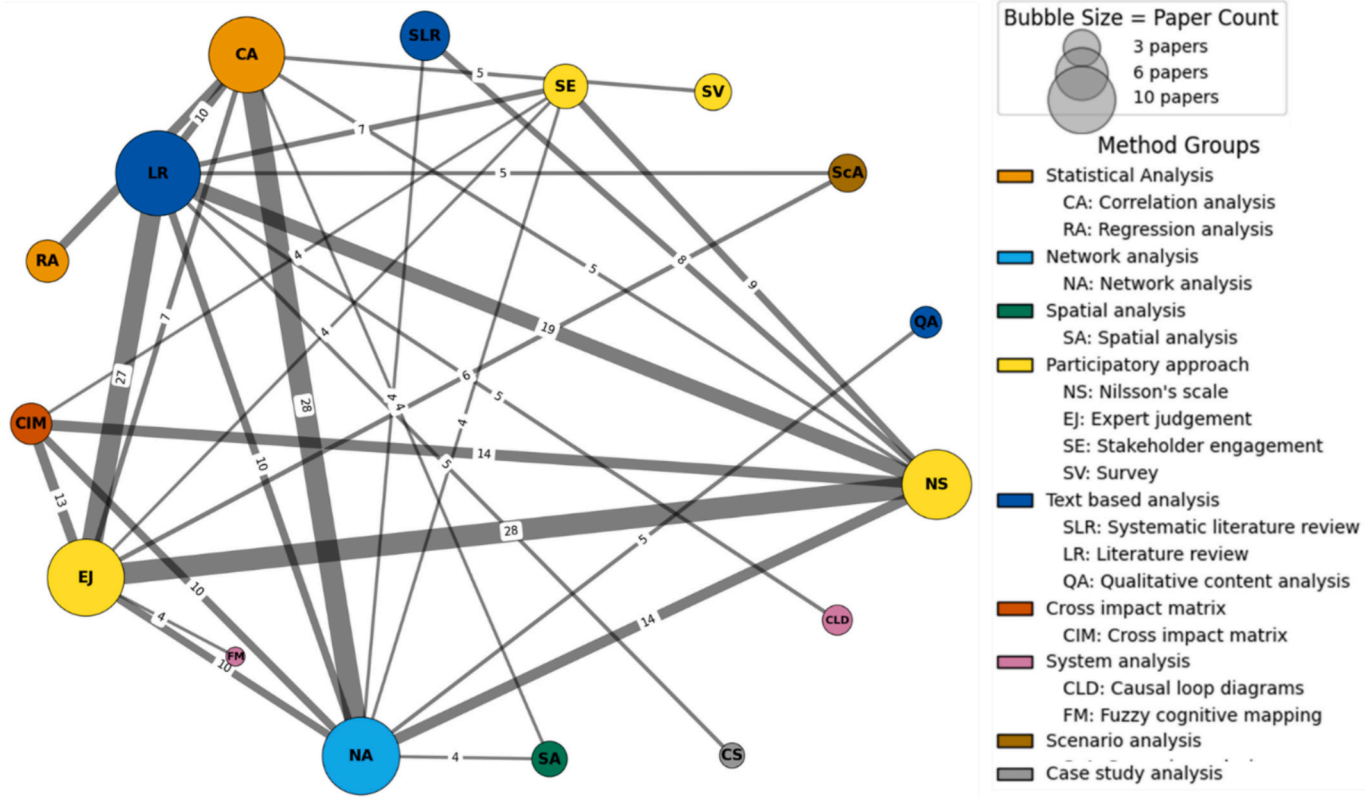

Fig. 6. The network diagram shows the frequency and co-application of methodological approaches to analyze SDG interactions. Node size corresponds to the number of studies employing each method, while edge thickness denotes the number of studies in which two methods co-occurred. Methods are categorized into each represented by a distinct color.

review (5 articles), respectively. The causal relations are represented using tools such as iModeler or Stella (Anderson et al., 2022; Neumann et al., 2018). Apart from scenario analysis conducted using fuzzy cognitive mapping (Ameli et al., 2023), only a few studies analyze the causal mechanisms using system dynamics modeling, such as the iSDG or the World3 model (Allen et al., 2024; Dörgő et al., 2018). Another small cluster involves spatial analysis, co-occurring with correlation analysis and network analysis (4 articles each), indicating an interest in spatial variations in interactions.

4. Discussion

Our systematic review synthesizes how SDG interactions have been conceptualized and analyzed across scales, methods, and SDG entities. Findings indicate a strong focus on certain interaction types and geographic contexts, imbalances in SDG representation, and limited use of indicator-level and transboundary analyses. This review also traced the evolution and co-occurrence of methods, highlighting the growing use of multi-method approaches. While some of these thematic and contextual gaps are previously noted, this review is the first to document their scale and texture using large-scale, systematic evidence. In doing so, it effectively supports evidence-based and context-aware research, which can potentially direct future research on SDG interactions.

4.1. Underrepresentation of interaction types

This review highlights an imbalance in the type of SDG interactions studied, with a dominant focus on interlinkages across goals, while intra-goal dynamics and transboundary effects remain significantly underexplored. The prioritization of certain interaction types underscores the need to broaden the scope of inquiry to better reflect the multidimensional and interdependent nature of SDGs. Thus, this imbalance limits our understanding of the full complexity of sustainable development, which requires attention to synergies and trade-offs within and across goals and borders.

Intra-goal dynamics (*intralinkages*) are rarely the primary focus, despite their critical importance. This is concerning, as each target within a goal holds equal weight and may conflict with other targets or indicators within the same goal. For instance, Pradhan et al. (2017) showed how trade-offs exist even within a single SDG, especially within indicators of SDGs 7, 8, 9, and 15. This emphasizes the importance of explicitly analyzing intralinkages, as their complex, multidimensional nature may otherwise be overlooked or subsumed under broader inter-goal assessments. Although often considered alongside interlinkages, few studies explicitly examine the internal coherence of individual goals. This can be potentially linked to the observation that most studies analyze interactions at the goal level instead of the target or indicator level. Indicators are often aggregated to the target and then the goal level. Conducting granular-level analysis requires the availability of data for each indicator, which could be a potential difficulty. However, no pattern was detected, which indicates hindrance due to methodological limitations.

The SDGs are primarily monitored and evaluated nationally without consideration for effects from other regions. National statistical systems often prioritize domestic indicators, neglecting external impacts, which makes it difficult to assess cross-border effects (Ino et al., 2022). The SDG framework itself doesn't consist of indicators or indices dedicated to tracking spill-overs, particularly those related to exports, capital flows, or foreign trades (Li et al., 2025). Although spatial econometric models are emerging as a valuable tool, there are no globally standardized models that can systematically identify, attribute, and isolate drivers or impacts across borders for the full range of economic, social, and environmental outcomes (OECD, 2025). The neglect of cross-border impacts reflects a lack of mechanisms to ensure policy coherence across jurisdictions, complications in establishing underlying causes, and political disinterest or biases. Difficulties in collecting cross-border data that vary across time and space also act as a hindrance (Kivimaa et al., 2025).

As a result, transboundary linkages are the least studied type of SDG interaction across all geographic scales. While previous research has noted the absence of global-scale spillover analyses (Fronza et al., 2023; Miola et al., 2019), our results show that a significant gap also remains at national and sub-national scales. Researchers have argued that spillover effects at the sub-national scale can affect opportunities to progress towards SDGs beyond national boundaries (Engström et al., 2021). This is concerning given the transboundary nature of sustainability challenges, including climate change, biodiversity loss, resource flows such as human migration, and pandemics. Research addressing the need for standardized indicators to assess countries' spill-over effects showed that vulnerable countries bear the environmental burdens of advanced economies, affecting their SDG scores (Chen, 2024). Without a stronger focus on these transboundary dynamics, the SDG framework risks reinforcing a national silo that ignores global interdependence.

External linkages are increasingly recognized, especially in the context of climate action and the global pandemic, as external entities; however, there has been a decline in their overall contribution in research since the previously noted trend (Bennich et al., 2023). Geopolitical conflicts and financial crises have still not been significantly accounted for. Some researchers noted that complications in the assessment of interactions are further added by intergenerational spill-overs, where present-day actions affect future generations (Assubayeva and Marco, 2024; Miola et al., 2019). Analysis focusing on this particular aspect was also not encountered in the relevant articles. Addressing this would require policies that take a long-term view and account for the cumulative impact of decisions.

4.2. Geographic biases in the literature

This review unveils a strong geographic concentration of studies, with limited representation at sub-national and regional levels. These geographic biases in research risk narrowing the global understanding of SDG synergies and trade-offs and may lead to policy recommendations that lack sufficient contextualization. While previous reviews have called for more local contextualization (Bennich et al., 2023; Breuer et al., 2019), our findings show that this is yet to materialize. Most studies still focus on national and global scales, despite growing evidence that interactions vary significantly across local contexts (Guan et al., 2025; Saiu et al., 2022; Zhang et al., 2025). A lack of data and research at the sub-national scale hinders the understanding of interactions at the local level (Pradhan et al., 2024). Besides data gaps, societal and institutional structures, as well as inadequate funding, also hinder the localization of the SDGs (Annan-Aggrey et al., 2021; Issa and El-Fadel, 2025). In some cases, there is also a misalignment between national-level policies and their implementation at the local scale. Differences in political discourses at the subnational scale also contribute to this (Beisheim et al., 2025). A bottom-up approach, with local reporting of SDG dynamics, monitoring, and evaluation by local communities or governance, can facilitate the institutional changes needed to accelerate progress towards the SDG framework (Bilsky et al., 2021).

National and sub-national studies are also geographically concentrated in a few countries, particularly upper- and middle-income economies like China and India, while low-income countries remain largely underrepresented. Previous studies also point to the limited involvement of lower-income countries in general SDG research (Confraria et al., 2024). Low-income countries face cuts in international aid and broader economic challenges (OECD, 2025), which can result in chronic underinvestment in research. Ineffective institutions, limited resources for data collection and monitoring, a lack of capacity building, and the unavailability of required technology also contribute to a narrow research avenue (Barbier and Burgess, 2021; Pyakurel and Marasini, 2021). China's dominance in SDG research is significant and has been previously noted (Yumnam et al., 2024). Investments in the Big Earth

Data program, as well as its application in evaluating SDG indicators (Guo, 2024), and annual reports, such as the Chinese Statistical Yearbook, help fill data gaps. This is also reflected in the methodological approaches being used, as it was observed that most analyses based in China employ quantitative-statistical methods. Interestingly, the majority of papers relying on spatial analysis are also based in China, due to the availability of geospatial data related to indicators. In contrast, the absence of the U.S. in interaction studies is noticeable, despite its global economic dominance, possibly due to limited SDG uptake in U.S. federal and state policy (Lynch and Sachs, 2021).

Regional-level SDG interactions are the least explored, with most studies focusing on the European Union. This is a critical gap, as regional analyses are essential for capturing socio-economic and political commonalities that shape SDG interactions. Research shows that universal SDG benchmarks may obscure regional differences and that context-specific prioritization is needed, as for example, analyses across OECD and non-OECD regions reveal significant variation in synergies and trade-offs among SDG targets (Bali Swain and Ranganathan, 2021). Similarly, regional-level analyses based on income variation reveal that the strength and nature of interactions shift significantly across income groups (Lusseau and Mancini, 2019; Warchold et al., 2021).

4.3. Thematic blind spots in SDG coverage

SDG coverage remains largely uneven in interaction research. SDGs tied to environmental services and basic needs (e.g., SDGs 2, 6, and 15) are analyzed most often, while goals on inequality, gender, peace, and partnerships (e.g., SDGs 5, 10, 16, and 17) are substantially underrepresented. This imbalance raises serious concerns about the comprehensiveness of current SDG interaction research. Moreover, the selection of SDGs for analysis often reflects the specific contexts in which interactions are observed, rather than a systematic approach to cover all 17 goals. One of the major challenges underlying these blind spots is an imbalance in the funding priorities. In the overall SDG research landscape, socially oriented goals remain among the least funded, placing them at a structural disadvantage in terms of influence and visibility (Dorta-González and Dorta-González, 2023; Varelas et al., 2025a). Being politically and socially complex, these goals involve power structure, governance, and rights issues, which are more sensitive to governments and funders. As a result, financing flows tend to favor goals with clearer economic returns, such as health, energy, and climate. SDG 16, for example, suffers from underfunding due to its unattractive risk–return profile for investors, limited private sector involvement, and reliance on weak funding channels, such as debt restructuring and selective ESG investment (Neher et al., 2025).

Governance and social justice issues are central to sustainable development, but are often excluded from modeling and systems analyses due to methodological challenges in integrating qualitative or intersectional data (Pradhan et al., 2024). Methodologically, these SDGs are less often modeled using IAMs, system dynamics, or equilibrium models, as their direct indicators or proxies are less suited to such frameworks' optimization (Kluck et al., 2025). The same reasons can also be extended to emerging geospatial methods. Descriptive statistical methods and qualitative approaches, however, were seen to be used effectively for mapping interactions across all SDGs. Beyond this, no clear methodological pattern emerged in the literature, as many articles use a multi-method approach to overcome such limitations. Overlooking the enabling role of SDGs 16 and 17 reflects a restrictive perspective.

Addressing these thematic imbalances is essential not only for equity but also for analytical accuracy. For example, integrating the gender dimension into scenario-based models enhances understanding of the challenges associated with climate change (Andrijevic et al., 2025). Aspects such as animal welfare, given its positive impacts on human and environmental well-being (Herdoiza et al., 2024), the incorporation of Indigenous knowledge systems (Yap and Watene, 2019), and the integration of tools like environmental impact assessment (Ravn Boess et al., 2021) remain largely absent from the SDGs. If left unaddressed, these thematic blind spots risk narrowing the scope of SDG interaction research and undermining its ability to capture the complex, interdependent, and systemic challenges that the 2030 Agenda addresses.

4.4. Methodological co-occurrence as a lens into analytical evolution

Although methods have diversified, the field remains dominated by text-based approaches and participatory methods. While participatory approaches are important for context-based studies, especially where statistical data are unavailable, they may introduce subjectivity and biases. In recent years, there has been a slight shift towards data-intensive statistical methods, spatial analysis, and systems thinking. Frequent use of correlation analysis, network analysis, cross-impact matrix methods, and participatory scoring frameworks has been noted previously (Assubayeva and Marco, 2024).

Co-occurrence analysis reveals that methods are increasingly combined to enhance analytical depth and normative relevance. The co-occurrence of Nilsson's scale, CIM, and network analysis was also noted by Bennich et al. (2023), indicating the complementary nature of these methods. However, this research does not examine the broader occurrence of statistical methods such as correlation analysis, PCA, and network analysis, or the co-existence of other methods with system analysis (causal loop diagrams and fuzzy cognitive mapping) and spatial analysis. Methodological innovation is needed beyond tool combination towards proper methodological integration. Interdisciplinary teams must co-design studies, selecting methods based on the research question and adapting them to the context. A combination of emerging methods, such as spatial analysis and systems thinking, is one such example (Cao et al., 2023).

Interaction strength, directionality, and causal mechanisms are central to understanding how synergies and trade-offs emerge, yet remain underexplored (Anderson et al., 2022; Xiao et al., 2023a, 2023b). Mere linkage of SDGs does not explain their underlying dynamics. Despite a recent increase in system-based approaches, they rarely address these aspects directly. Future research should place greater emphasis on second-order influences and underlying causal mechanisms between the SDGs. Similarly, temporal dynamics remain underexplored, despite their relevance for shifting synergies and trade-offs over time (Kroll et al., 2019). The dynamic nature of sustainability challenges calls for methods that assess how interactions evolve under different scenarios. IAMs and system dynamics modeling can be leveraged to support this shift. In parallel, recent studies point towards the untapped potential of AI and LLM in SDG research (Benjira et al., 2025; Varelas et al., 2025b), yet remain underutilized in interaction research.

4.5. Limitations

Despite providing insights into SDG interactions, certain limitations are to be acknowledged. First, the analysis draws exclusively from English-language literature indexed in Scopus and Web of Science, excluding grey literature. This may exclude valuable regional or local knowledge. Most reports on the SDGs are published at both national and international levels, providing a synthesis of findings and monitoring. However, the exclusion of grey literature, which contributes to methodological developments related to the interactions, can create biases in the results. For example, if the policymakers and administrators are still heavily relying on participatory or qualitative approaches, then that wouldn't be covered comprehensively. Geographic biases, such as reports or literature generated by local governments or organizations analyzing interactions, are also excluded. Future studies can also incorporate these studies or reports to gain a broader perspective. However, the inclusion of studies across geographic scales and contexts may mitigate this limitation. Second, potential bias may arise as categories such as type of interactions and methods rely on author-reported descriptions, which are inconsistent. Transparent selection criteria and

systematic coding of multiple data extraction points ensure a robust synthesis. Third, while this review maps the frequency and co-occurrence of methods, it does not assess their comparative effectiveness or the robustness of their results. For example, the common pairing of network analysis and literature review may enhance analytical credibility. However, without standardized evaluation metrics, it is difficult to determine whether these combinations are methodologically sound or simply prevalent. Finally, this review focuses explicitly on SDG-labeled research. Interactions between the social, environmental, and economic aspects of sustainability are also studied and reported outside the SDG framing (Miladinov, 2023; Onaran et al., 2022; Williams et al., 2021). As this study focuses explicitly on the 2030 Agenda, this remains outside the scope of the current work. However, these studies could be considered in future work to enhance the understanding of SDG interactions.

4.6. Implications

Transforming the state of the art into policy requires communicating evidence-based findings from research. This review on SDG interaction studies aims to contribute to these efforts. As SDG interactions play an essential role in the systematic prioritization of SDGs (Anderson et al., 2022), gaining insights into the status and potential improvements in existing research is essential. Based on these findings, several priorities for future research can be identified. Expanding the geographic and thematic scope of SDG interaction studies remains a priority, including greater representation of low-income countries, underrepresented regions, and a focus on gender, inequality, governance, and partnership. Addressing these gaps will require more inclusive and innovative approaches that integrate context-specific knowledge with data-intensive methods. Studies should move beyond goal-level analysis and adopt more granular approaches by considering targets and indicators.

Future research could also expand upon recent SDG interaction mapping efforts (Bennich et al., 2023) to deepen understanding of how synergies and trade-offs manifest across different SDG entities. Building on the broader patterns identified in this review, subsequent analyses could explore whether consistent interaction patterns emerge or if these relationships remain highly context-dependent. Such work would strengthen the empirical foundation for integrating SDG goals and targets into policy and planning, helping identify where sector collaboration can maximize synergies and minimize trade-offs.

Although global databases, such as the UN SDG indicators and the World Bank's indicators, remain crucial, they should be complemented with sub-national, qualitative, and citizen-generated data. Beyond conventional surveys or focused group discussions, internet-based platforms, social media reporting, and other cost-effective methods can be leveraged. The citizen science approach can also be used for capacity building at the local scale, helping evaluate interactions and inform the implementation of national policies (Fraisl et al., 2025). Effective collaboration is crucial for achieving global goals, particularly between high-income countries and low-income countries. This should go beyond providing direct financial support and be seen as an exchange of expertise, data, technology transfer, and capacity building (Yumnam et al., 2024).

When formulating policies, a shift towards systems thinking and an assessment of both direct and indirect interactions are essential for understanding the causal mechanisms underlying them. These can be further investigated by combining different causal inference methods, such as quasi-experimental designs or fixed panel models (Henningsen et al., 2025), with system dynamic models, IAMs, or Agent-Based Modeling to capture feedback loops, simulate long-term scenarios, and assess policy trade-offs and synergies across multiple SDGs. Correlation analysis can be accompanied by quantifying the directionality of interactions with the transfer entropy method (Warchold and Pradhan, 2025). Advancements in AI and machine learning techniques, especially in LLMs, for drawing causal inferences (Chernozhukov et al., 2024) can co-occur with the citizen science approach for processing unstructured data, extracting causal patterns, and scaling insights for interactions.

Future studies should pay closer attention to spillover effects by examining how policies or developments in one region impact progress in another, and how transboundary governance can more effectively manage shared risks and responsibilities. This will require coordinated data collection and analysis across regions and sectors to ensure coherent and informed decision-making. Qualitative case studies or game theory approach can be combined with Multi-Regional Input-Output (MRIO) models or remote-sensing methods to assess cross-border trade or supply chains, providing both quantitative flows of resources and socio-political context. Potential directions could also include the creation of standardized indicators that can be used to evaluate resource flows based on context and scale.

Beyond outlining future directions, it is essential to critically evaluate what the current discourse on SDG interaction research implies for the transformative ambition of the 2030 Agenda. While a wide range of methods is applied, research agendas are often shaped by what is most measurable or fundable, privileging indicator coverage and tractable comparisons. This orientation can draw attention away from the institutional capacities and power relations through which trade-offs are negotiated and priorities set, and it leaves limited room for context-specific perspectives from low-income and local settings where implementation challenges are most acute. It also engages only lightly with the interdependencies and spillovers that link regions. By prioritizing measurability over explanation and treating governance as a technical management rather than a contested process, current approaches risk reinforcing silos, downplaying the roles of institutions and partnerships, and overlooking the shocks and crises that reconfigure development pathways. Unless these tendencies are addressed, SDG interaction research may continue to advance analytically while drifting from the systemic transformations it seeks to support.

5. Conclusion

This systematic review provides a comprehensive synthesis of how SDG interactions have been conceptualized and analyzed since their inception. Doing so emphasized the need to expand the scope of inquiry to better reflect the multidimensional and interdependent nature of sustainable development. By supporting a more inclusive and analytically grounded sustainability science, this review can inform researchers and policymakers, enabling a shift from selective to systematic SDG prioritization. The findings reveal a dominant emphasis on interlinkages across goals, with limited attention to intra-goal dynamics and transboundary effects. SDGs related to equity, governance, and institutional development – SDGs 5, 10, 16, and 17 – remain underrepresented, as do local and regional scales of analysis. This points to a systemic bias in the research landscape and highlights the need for greater representation of studies based in lower-income countries. Methodological practices are increasingly integrative, marked by frequent co-application of approaches. However, further research is needed to advance innovative and multi-method approaches, especially to understand the causal mechanisms behind the interactions. Addressing these potential opportunities for improvement is essential if SDG research is to fulfil its promise of supporting truly integrated, equitable, and actionable pathways to sustainability.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2025.108274.

Data availability

Data has been shared as supplementary files.

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