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Synergies and trade-offs across sustainable development goals: A novel method incorporating indirect interactions analysis

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Abstract

The sustainable development goals (SDGs) are presented as significantly interacted. Yet most studies only investigated the direct interactions of SDG targets, and indirect interactions, that is, the interlinkages transmitted through one or more mediums, should also be considered to obtain more accurate interaction estimation and more scientific policy decisions. We first made a methodological contribution by proposing a plus-minus decision-making trial and evaluation laboratory model, which can consider not only the direct synergies and trade-offs but the indirect ones. Then, based on this proposed method, we navigated the complicated network across the SDGs considering both direct and indirect interactions, find out the key interactive ones with a visually directed graph, obtain the weights of each SDG, and define the best governance structures to capitalize on synergies and minimize trade-offs. Results show that, when incorporating indirect interactions, the share of synergy effect of SDGs dominates the total influence, taking up to 98.33%, suggesting that the achievement of the 2030 Agenda can be facilitated through interactions. Although all SDGs should be equally addressed by 2030 suggested by the United Nations, equal importance across 17 SDGs does not mean we have to make the same efforts in achieving each SDG, and SDG 4 and SDG 13 are the top priority to tap into these interaction potentials. Our interdisciplinary analysis across economic growth, social inclusion, and environmental protection provides a science-driven reference for all UN member states to facilitate achieving the SDGs by maximizing the synergies and minimizing the trade-offs.

KEYWORDS

indirect interaction, plus-minus decision-making trial and evaluation laboratory model, sustainable development goals, synergy, trade-off

1 | INTRODUCTION

The sustainable development goals (SDGs) proposed by the United Nations are implemented by all United Nations Member States to achieve sustainability and stimulate action from 2016 to 2030 (Xiao et al., 2022). The SDGs can be a report card to have a clear picture of where we stand and can be a powerful tool to support policymakers for management (Schmidt-Traub et al., 2017; Wiedmann & Allen, 2021). However, the achievement of the SDGs is not simply about ticking off targets one by one. The SDGs are presented as significantly interacted (e.g., supportive and conflicting relationship) (McGowan et al., 2019; Nash et al., 2020; Zhang et al., 2019; Zhu et al., 2022). Exploring the interactions among the SDGs is critical to realizing the full potential, and to guarantee that progress gained in some SDGs does not undermine the achievement of other SDGs (Lusseau & Mancini, 2019; McGowan et al., 2019; Zhang et al., 2021).

There is a total of 17 SDGs incorporating 169 targets used to measure the degree of achievement (Xiao et al., 2022; Xu et al., 2020). Target-level analyses of the interaction across the SDGs have been attracted increasing attention (Nerini et al., 2019; Nilsson et al., 2016) and investigated for some kinds of subject matter with quantitative and qualitative methods. Quantitative analyses of interlinkages among the SDG targets generally adopted indicator data of a set of SDG targets to investigate the statistical correlation such as Spearman correlation analysis (Fonseca et al., 2020; Lusseau & Mancini, 2019; Pradhan et al., 2017). However, the interaction analysis using the quantitative method generally explore the correlation relationship but not the causality relationship, suggesting we cannot identify the role of an SDG as an influence transmitter or receiver (Kroll et al., 2019). Influence transmitters suggest the SDGs that generate influence and influence receivers mean the SDGs that receive influence. Qualitative analyses generally adopted expert elicitations and surveys and search for published evidence of interlinkages among targets. Therefore, different from quantitative analyses, qualitative analyses can describe causality relationship among SDGs. Numerous studies have map the interactions of targets based on qualitative analyses (Alcamo, 2019; Fuso Nerini et al., 2018; Kroll et al., 2019; Le Blanc et al., 2017; Mantlana & Maoela, 2020; Nerini et al., 2019; Pham-Truffert et al., 2020; Thacker et al., 2019; Warchold et al., 2021).

However, the above-mentioned studies only investigated the direct interactions of SDG targets. The interlinkage of the SDGs can be indirect, suggesting that the interlinkage can be transmitted through one or more mediums. For example, the deployment of renewable energy (Target 7.2) can reduce greenhouse gas emissions (Target 13.2), and climate mitigation has synergies with targets concerning poverty reduction (Target 1.1; Nerini et al., 2019; Shafiei & Salim, 2014). Thus, Target 7.2 can exert indirect interactions with Target 1.1. Indirect interactions should also be taken into consideration in SDG interaction analysis, which can provide more accurate interaction estimation and more scientific policy decisions (Anderson et al., 2022; Weitz et al., 2018). Weitz et al. (2018) investigated how interactions ripple through the system by looking at second-order interactions across 34 SDG targets (Weitz et al., 2018). This can be regarded as partial indirect interaction analysis since they calculated the indirect interactions considering only one medium and did show how to deal with the situations with more than one mediums. Anderson et al. (2022) used correlation analysis to extract 97 positive pairs and 34 negative pairs of SDG targets, identify the influence direction of these pairs, and lastly used iMODELER software to reveal the relative influence of SDG targets on the overall achievement of the 2030 Agenda (Anderson et al., 2022). This iMODELER software can consider the feedback loops (indirect interaction) across SDG targets (Anderson et al., 2022). However, this study did not answer how SDGs positively and negatively affect each other in direct and indirect ways. Therefore, the detailed components of the total influence of each SDG are still unknown, such as direct synergy effects, indirect synergy effects, direct trade-off effects, indirect trade-off effects, total effects as an influence transmitter, and total effects as an influence receiver.

Another challenge is that we know little about the importance level (weight) of each SDG. Obtaining the weight is a critical step in multi-criteria decision making (Wątróbski et al., 2019), and is important information for policymakers to understand which SDGs should be the top priority to facilitate the achievement through interaction and which SDGs are less effective in tapping into the full potential of interactions. Although there are a lot of methods to obtain the weight of different criteria (e.g., analytic hierarchy process, analytic network process, and best worst method) (Wątróbski et al., 2019), these methods can not consider the criteria that have causal relationship. For the decision-making trial and evaluation laboratory (DEMATEL) method, it can deal with the causal relationship problem, but traditional DEMATEL method treats the influence level between two criteria as a black box, with the components of the influence (e.g., synergy effects and trade-off effects) unknown. The United Nations suggested there is no a priori reason to give one SDG greater importance than another, so all 17 SDGs should be equally treated to convey the importance of integrated solutions that equally address all 17 SDGs (Schmidt-Traub et al., 2017; Xu et al., 2020). However, equal importance across 17 SDGs does not mean we have to make the same efforts in achieving each SDG. The actions in improving the score of one SDG can positively or negatively affect the progress of other SDGs, so we can make good use of the interactions between different SDGs to facilitate the joint achievement of all SDGs by 2030.

To close these two research gaps, this study first made a methodological contribution by proposing a plus-minus decision-making trial and evaluation laboratory model (plus-minus DEMATEL), which can consider not only the direct synergies and trade-offs but the indirect ones. This novel model overcomes the disadvantage of traditional DEMATEL method that treats the influence level between two factors as a black box, with the components of the influence (e.g., synergy effects and trade-off effects) unknown. The proposed model pushes the knowledge frontier regarding the field of multi-criteria decision-making. Then, based on this proposed method, we navigate the complicated network across the SDGs considering both direct and indirect interactions, find out the key interactive ones with a visually directed graph, obtain the weights of each SDG, and define the best governance structures to capitalize on synergies and minimize trade-offs. Our multidisciplinary results consider the full spectrum of synergies and trade-offs across the SDGs, which are basic for interaction-related studies and science-policy conversations of multiple disciplines and sectors.

2 | LITERATURE REVIEW

Target-level analyses of the interaction across the SDGs have been called for (McGowan et al., 2019; Nerini et al., 2019; Nilsson et al., 2016) and completed for several kinds of subject matter, both quantitatively and qualitatively (Fuso Nerini et al., 2018; Lusseau & Mancini, 2019; Mantlana & Maoela, 2020; Pradhan et al., 2017).

Quantitative analyses of interlinkages among the SDG targets generally examine the statistical correlation based on indicator data of a set of SDG targets (e.g., Spearman correlation analysis and linear mixed-effect models)(Lusseau & Mancini, 2019; Pradhan et al., 2017). For example, Lusseau and Mancini (2019) estimated the positive and negative correlation across 71 SDG targets using linear mixed-effect models based on indicator data released by the World bank (Lusseau & Mancini, 2019). Pradhan et al. (2017) used Spearman correlation method to analyze the interactions across 122 indicators data provided by UN Statistics Division (Pradhan et al., 2017). Ronzon and Sanjuán (2020) used Spearman correlation analysis to study 54 bio-economy-related SDGs indicators for 28 EU Member States (1990–2018)(Ronzon & Sanjuán, 2020).

However, the interaction analysis using the quantitative method fails to explore the causality relationship (influence transmitter or receiver). Thus, numerous studies have map the interactions of targets based on qualitative analyses (Alcamo, 2019; Fuso Nerini et al., 2018; ISC, 2017; Le Blanc et al., 2017; Mantlana & Maoela, 2020; Nerini et al., 2019; Thacker et al., 2019; UN-Water, 2016). Qualitative analyses generally adopted expert elicitations and surveys and search for published evidence of interlinkages among targets. Existing published studies about interactions of SDG targets included SDG 2 (interaction with partial SDG targets); ISC, 2017), SDG 3 (interaction with partial SDG targets; International Science Council (ISC, 2017), SDG 6 (Alcamo, 2019; UN-Water, 2016; Wang et al., 2022), SDG 7 (only as a receiver; Fuso Nerini et al., 2018), SDG 9 (only as a transmitter; Mantlana & Maoela, 2020; Thacker et al., 2019), SDG 13 (only as a transmitter; Nerini et al., 2019), and SDG 14 (ISC, 2017; Le Blanc et al., 2017; Wang et al., 2022). Pham-Truffert et al. (2020) conducted a systematic literature review by searching the keywords “SDG” and “interaction,” or very close synonyms to summarize the synergy and trade-off linkages across 126 SDG targets (Pham-Truffert et al., 2020). This literature review included 65 UN reports and international scientific assessments as well as 112 scientific articles that are published before early 2018 (Pham-Truffert et al., 2020).

Another challenge is that the interlinkage of the SDGs can be indirect, suggesting that the interlinkage can be transmitted through one or more mediums. The decision-making trial and evaluation laboratory (DEMATEL) method can be regarded as an effective tool to investigate the causal influence among factors within a complicated system that can consider indirect interactions (Gabus & Fontela, 1972; Gabus & Fontela, 1973; Si et al., 2018). A visual directed graph can be drawn to find out the significant ones and can separate involved factors into influence delivers and influence receivers (Si et al., 2018). The weight of each factor can also be obtained based on the degree of the cause-effect relationship, and then can be applied to the field of multiple-criteria decision-making (Si et al., 2018). Due to its powerful capabilities, the DEMATEL method has been widely applied to a variety of fields in recent decades, such as supply chain management (Gandhi et al., 2016; Najmi & Makui, 2012; Shafiee et al., 2014), product development (Wang & Hsueh, 2013; Wang & Shih, 2013), and enterprises performance(Alaei & Alroaia, 2016; Shaik & Abdul-Kader, 2014). DEMATEL can also been integrated with a variety of other methods or tools in decision making fields, such as fuzzy DEMATEL (Wu & Lee, 2007), large group linguistic Z-DEMATEL (Jiang et al., 2020), ANP-DEMATEL (Azizi et al., 2014), and other DEMATEL (Ding & Liu, 2018; Liu et al., 2015; Liu et al., 2017; Liu et al., 2019).

However, traditional DEMATEL methods treat the influence between two factors as a black box, with the components of the influence (e.g., synergy effects and trade-off effects) unknown. The trade-offs and synergies among factors are quite common in the real world and sometimes they happen simultaneously (Bisaga et al., 2020; Nilsson et al., 2016). Regarding trade-off effects, there exists the potential conflicts between environmental protection and economic development (Dinda, 2004), global warming and industrialization process (Lin & Zhu, 2017), the resource curse theory regarding resource abundance and economic growth (Shao & Yang, 2014; Zhang & Brouwer, 2020), and quality-quantity trade-off theory in fertility choice (Becker, 1960; Doepke, 2015). For synergy effects, examples can be higher quality of governance accompanied by more economic benefits (Boschini et al., 2007) and promotion of renewable energy development followed by better air quality and human health conditions. A growing number of studies have found that the 169 targets under the 17 SDGs included plenty of such trade-offs and synergies (Fader et al., 2018; Hegre et al., 2020; Lusseau & Mancini, 2019; McGowan et al., 2019). Existing methods cannot incorporate indirect synergies and trade-offs in the total influence, which make it difficult to navigate this complicated relationship network, cause inaccurate estimation of interactions, and even mislead policy decisions.

3 | DATA AND METHODOLOGY

3.1 | Construction of direct interaction network of the SDGs

In the global indicator framework, there are specific targets under each SDG used to measure the degree of achievement. There is a total of 17 SDGs incorporating 169 targets (Xiao et al., 2022; Xu et al., 2020). Like some previous studies (Blanc, 2015; Pham-Truffert et al., 2020), our analysis did not include the interactions of SDG 17. One reason is that SDG 17 is related to the so-called “means of implementation” and aims to enhance international cooperation to achieve all the other SDGs (Pham-Truffert et al., 2020). It is challenging to apply the aforementioned methodology to SDG targets regarding means of implementation. However, it does not mean that SDG 17 does not deserve investigation and linkages across SDGs can be generated through SDG 17. Another reason is that this study concentrates on cross-thematic connections. Therefore, a total of 150 targets under 16 SDGs are incorporated for interaction analysis.

This study first constructed two matrixes: one is a synergy matrix and the other is a trade-off matrix. Then, we analyzed a body of evidence addressing two intersecting questions: (A) Can the status of targets be influenced by the progress of a goal? and (B) Is the influence identified as synergy effects or trade-off effects? Synergies indicate that progress in one goal promotes progress in another, while trade-offs refer to progress in one goal hindering progress in another. For question (A), if there are no interactions, we input 0 in both the synergy matrix and trade-off matrix. In the condition that interaction exists, we next answer question (B). If the influence is synergies or trade-offs, we input 1 or −1 in the corresponding matrix. The interactions can be identified as synergies in some cases and trade-offs in other cases. For example, actions on climate change can generate synergistic impacts on SDG 2.1 by improving agricultural productivity and food security, whereas these actions can also generate trade-off impacts by limiting options in what kinds of food are produced (e.g., low-carbon food production)(Nerini et al., 2019). This study took both situations into consideration by inputting 1 in the synergy matrix and inputting −1 in the trade-off matrix. Note that the interaction is identified based on the causal relationship instead of the correlation relationship.

Pham-Truffert et al. (2020) has done a systematic literature review in early 2018 and presented an interactive repository of SDG interactions, which records the causal relationship across all SDG targets covering 17 SDGs (exclude the 41 "lettered" targets from SDG 1 to SDG 17 or the so-called "means of implementation" targets) by reviewing 65 global scientific assessments and UN flagship reports as well as 112 relevant scientific articles. Therefore, this study included this interactive repository of SDG interactions as the main source to construct synergy matrix and trade-off matrix. For the cells of the matrixes that were still blank, we included some other studies about interaction to fill the blank by searching specific SDGs. Four conditions should be met at the same time to find the qualified studies: (1) The studies should include target-level interaction under the progress of each SDG (2) The interaction can be categorized into two groups (synergic links and trade-off links) (3) The interaction is directional, suggesting we can categorize their roles as influence receivers or transmitters. (4) The detailed interaction data is open to the public instead of being a black box. A small number of studies turned out to be particularly significant sources of information about synergic and trade-off relationship with causal relationship, that is SDG 2 (interaction with partial SDG targets; ISC, 2017), SDG 3 (interaction with partial SDG targets; ISC, 2017), SDG 6 (Alcamo, 2019; UN-Water, 2016; Wang et al., 2022), SDG 7 (only as a receiver; Fuso Nerini et al., 2018), SDG 9 (only as a transmitter; Mantlana & Maoela, 2020; Thacker et al., 2019), SDG 13 (only as a transmitter; Nerini et al., 2019), and SDG 14 (ISC, 2017; Le Blanc et al., 2017; Wang et al., 2022).

3.2 | The plus-minus decision-making trial and evaluation laboratory model

The DEMATEL method can be regarded as an effective tool to investigate the causal influence among factors within a complicated system (Gabus & Fontela, 1972, 1973; Si et al., 2018). Selection of data is a crucial step in constructing a reliable interaction network across SDGs and ensuring scientific findings (Warchold et al., 2022). The identification of this causal relationship is the foundation to conduct traditional

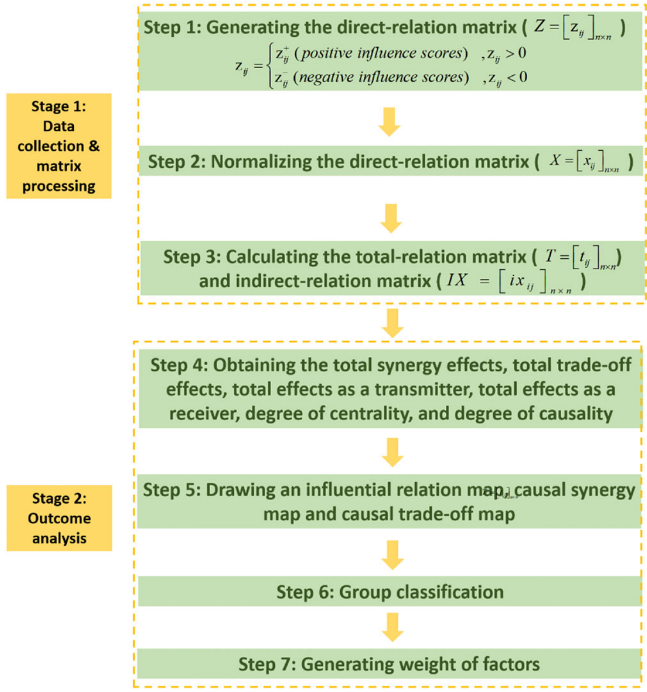

FIGURE 1 Flowchart of the proposed plus-minus DEMATEL model. The seven steps of the plus-minus DEMATEL shown in methodology section can be visualized by this flowchart [Colour figure can be viewed at wileyonlinelibrary.com]

DEMATEL method and draw an influential relationmap. The causal data used in this study were based on Section 3.1. Traditional DEMATEL method treats the influence level between two factors as a black box, with the components of the influence (e.g., synergy effects and trade-off effects) unknown. To overcome this disadvantage, this study proposes a plus-minus DEMATEL, which can incorporate indirect synergies and trade-offs in the total influence.

The procedures of this proposed model have seven steps, which can be visualized in Figure 1. These seven steps are divided into two stages. Stage 1 is about data collection & matrix processing, which includes steps 1–3. Stage 2 is about outcome analysis, which includes steps 4–7. This proposed model can be regarded as an effective tool to illustrate the causal influence structure of components, including synergies and trade-offs, within a complex system (see step 4), find out the significant ones with a visually directed graph (see step 5), group classification (see step 6). The weight of each factor can also be obtained based on the degree of the cause-effect relationship (see step 7), and then can be applied to the field of multi-criteria decision-making (Shao et al., 2020; Si et al., 2018).

Step 1 (Generating the direct-relation matrix $Z=[z_{ij}]_{n\times n}$ based on the linking structure across SDGs): z_{ij} is the elements of a matrix, representing the degree to which one SDG negatively or positively influences another SDG. In the direct-relation matrix, the row indicates influence transmitter, and the column indicates influence receiver. In the global indicator framework, there are specific targets under each SDG used to measure the degree of achievement and a total of 150 targets under the 16 SDGs. z_{ij} equals the number of SDG

TABLE 1 Description of influence level for the plus-minus DEMATEL model

Numeral	Definition
−4	Very high negative influence
−3	High negative influence
−2	Medium negative influence
−1	Low negative influence
0	No influence
1	Low positive influence
2	Medium positive influence
3	High positive influence
4	Very high positive influence

targets under SDG j that are influenced by SDG i. If the target of SDG j is identified as a synergy receiver, we add 1 to z_{ij}. The more positive connections SDG j has, the higher z_{ij} will be. By contrast, if the linkage is recognized as trade-off effects, we minus 1 from z_{ij}. After screening all the targets of 16 SDGs, we can obtain the direct-relation matrix $Z=\left[z_{ij}\right]_{n\times n}$, as follows:

$$z_{ij}=\begin{cases} z_{ij}^{+},\ z_{ij}>0 \\ z_{ij}^{-},\ z_{ij}<0 \end{cases} \quad (1)$$

where z_{ij} can be a positive value ($z_{ij}^{+}>0$) or negative value ($z_{ij}^{-}<0$), which indicates positive influence scores and negative influence scores, respectively.

Alternative Step 1 (Generating the direct-relation matrix $Z=\left[z_{ij}\right]_{n\times n}$ based on opinions of experts): In traditional DEMATEL model, the direct-relation matrix is based on opinions of experts (Si et al., 2018). However, the step 1 is only suitable for the topics related to the SDGs because its direct-relation matrix $Z_k=\left[z_{ij}\right]_{n\times n}$ is based on the linking structure among the SDGs. As such, to increase the generality of this proposed model, we also provide an alternative step to generate the direct-relation matrix, which is based on opinions of experts and can be applied to broader research fields that include multiple factors. This direct-relation matrix is formed based on the opinions of experts on the influence level instead of the linking structure among the SDGs. This study only adopted step 1 to generate the direct-relation matrix instead of alternative step 1 since the opinions of experts are less objective.

Assume that there are l experts $E=\{E_1, E_2, ..., E_l\}$ in a decision group and n factors $F=\{F_1, F_2, ..., F_n\}$ in a system. These experts are asked to evaluate the direct influence that factor F_i has on F_j based on an integer scale shown in Table 1. In traditional DEMATEL method, experts will be asked to indicate the influence level based on 5-point scales, that is no influence (0), low influence (1), medium influence (2), high influence (3), and very high influence (4) (Si et al., 2018). In our proposed plus-minus DEMATEL, the pair-wise influence scale is designated to have nine levels since we consider both synergistic effects and trade-off effects, where the scores of (−1, −4), 0, and (1, 4) denote negative influence, no influence, and positive influence, respectively, as follows:

Then, the individual direct-influence matrix $Z_k=\left[z_{ij}^{k}\right]_{n\times n}$ provided by the kth expert can be formed, with all principal diagonal elements equal to zero. z_{ij}^{k} is the component of the direct-influence matrix of expert E_k, indicating the degree to which factor F_i influences factor F_j based on the evaluation of the expert E_k. The direct-influence matrix $Z=\left[z_{ij}\right]_{n\times n}$ of a group with l experts can be obtained, as follows:

$$z_{ij}=\frac{1}{l}\sum_{k=1}^{l} z_{ij}^{k}, i,j=1,2,...,n. \quad (2)$$

where z_{ij} can be a positive value ($z_{ij}^{+}>0$) or negative value ($z_{ij}^{-}<0$), which indicates positive influence scores and negative influence scores, respectively.

Step 2 (Normalizing the direct-relation matrix to obtain $X=\left[x_{ij}\right]_{n\times n}$): when the group direct-influence matrix $Z=\left[z_{ij}\right]_{n\times n}$ is acquired, the normalized direct-influence matrix $X=\left[x_{ij}\right]_{n\times n}$, in which all principal diagonal elements are equal to zero, can be achieved by using the following equations.:

$$X=\frac{Z}{s} \quad (3)$$

$$s=\max\left(\max_{1\le i\le n}\sum_{j=1}^{n} z_{ij}^{+}, \max_{1\le i\le n}\sum_{j=1}^{n}\left|z_{ij}^{-}\right|, \max_{1\le j\le n}\sum_{i=1}^{n} z_{ij}^{+}, \max_{1\le j\le n}\sum_{i=1}^{n}\left|z_{ij}^{-}\right|,\right) \quad (4)$$

where x_{ij} can be a positive value ($x_{ij}^{+}>0$) or negative value ($x_{ij}^{-}<0$). All elements in the matrix X comply with $0\le\sum_{i=1}^{n} x_{ij}^{+}, \sum_{i=1}^{n}\left|x_{ij}^{-}\right|, \sum_{j=1}^{n} x_{ij}^{+}, \sum_{j=1}^{n}\left|x_{ij}^{-}\right|\le 1$.

Step 3 (Calculating the total-relation matrix $T=\left[t_{ij}\right]_{n\times n}$ and indirect-relation matrix $IX=\left[ix_{ij}\right]_{n\times n}$): using the normalized direct-influence matrix X, the total-influence matrix $T=\left[t_{ij}\right]_{n\times n}$ is then computed by summing up the direct effects and all of the indirect effects by the following equation (Gabus & Fontela, 1972, 1973; Si et al., 2018):

$$T=\lim_{h\to\infty}\left(X+X^2+X^3+...+X^h\right)=X(I-X)^{-1} \quad (5)$$

$$IX=T-X=X(I-X)^{-1}-X \quad (6)$$

where I is denoted as an identity matrix. t_{ij} and ix_{ij} indicate the total-relation coefficient and indirect-relation coefficient. They can be a positive value ($t_{ij}^{+}>0; ix_{ij}>0$) or negative value ($t_{ij}^{-}<0; ix_{ij}<0$) which indicates positive influence scores and negative influence scores, respectively.

Step 4 (Obtaining the total synergy effects (SE), total trade-off effects (TE), total effects as a transmitter (TD), total effects as a receiver (TR), degree of centrality ($TD+TR$), and degree of causality ($TD-TR$)): the vectors R^{+}, R^{-}, D^{+}, and D^{-}, representing the sum of the positive values of rows, negative values of rows, positive values of columns, and negative values of columns from the total-influence matrix T, respectively. They are defined by the following equations:

$$D^{+}=\left[d_j^{+}\right]_{n\times 1}=\left[\sum_{i=1}^{n}t_{ij}^{+}\right]_{n\times 1},\ D^{-}=\left[d_j^{-}\right]_{n\times 1}=\left[\sum_{i=1}^{n}t_{ij}^{-}\right]_{n\times 1} \tag{7}$$

$$R^{+}=\left[r_i^{+}\right]_{1\times n}=\left[\sum_{j=1}^{n}t_{ij}^{+}\right]_{1\times n}^{T},\ R^{-}=\left[r_i^{-}\right]_{1\times n}=\left[\sum_{j=1}^{n}t_{ij}^{-}\right]_{1\times n}^{T} \tag{8}$$

where d_i is the column sum in the matrix T and depicts the sum of direct and indirect effects that factor F_i receives from the other factors. Similarly, r_i is the ith row sum in the matrix T and displays the sum of the direct and indirect effects dispatched from factor F_i to other factors.

The study proposes two indicators to denote the total synergy effects (SE) and total trade-off effect (TE) of a factor, respectively. Let $i=j$ and $i,j\in\{1, 2, ..., n\}$. The SE and TE of factor i can be obtained as follows:

$$SE=[se_i]_{n\times 1}=\left[d_i^{+}\right]_{n\times 1}+\left[r_i^{+}\right]_{1\times n}^{T} \tag{9}$$

$$TE=[te_i]_{n\times 1}=\left[d_i^{-}\right]_{n\times 1}+\left[r_i^{-}\right]_{1\times n}^{T} \tag{10}$$

The higher the value of SE is, the more synergy effects are received from and delivered to other factors. Also, a higher TE indicates that stronger trade-off effects are received from and delivered to other factors. More attention can be paid to enhance factors with higher SE, which can help to facilitate improvement of the overall performance, while a close eye should be kept to mitigate or even avoid the trade-off effects of factors with a high TE.

We further define the total effects as a transmitter (TD) and the total effects as a receiver (TR) as follows:

$$TD=[td_j]_{n\times 1}=\left[d_j^{+}\right]_{n\times 1}-\left[d_j^{-}\right]_{n\times 1} \tag{11}$$

$$TR=[tr_i]_{1\times n}=\left[r_i^{+}\right]_{1\times n}-\left[r_i^{-}\right]_{1\times n} \tag{12}$$

where TD and TR indicate the total effects, including synergy effect and trade-off effect, that is delivered to or received from other factors, respectively. When TD becomes higher, it means that this factor has more influence on others. Similarly, a higher TR indicates that this factor is more likely to be affected by others.

Let $i=j$ and $i,j\in\{1, 2, ..., n\}$. The degree of centrality ($TD+TR$) and degree of causality ($TD-TR$) can be obtained as follows:

$$TD+TR=[a_j]_{n\times 1}=\left[d_j^{+}\right]_{n\times 1}-\left[d_j^{-}\right]_{n\times 1}+\left[r_i^{+}\right]_{1\times n}^{T}-\left[r_i^{-}\right]_{1\times n}^{T} \tag{13}$$

$$TD-TR=[b_j]_{n\times 1}=\left[d_j^{+}\right]_{n\times 1}-\left[d_j^{-}\right]_{n\times 1}-\left[r_i^{+}\right]_{1\times n}^{T}+\left[r_i^{-}\right]_{1\times n}^{T} \tag{14}$$

Step 5 (Setting the thresholds and drawing an influential relation map, causal synergy map and causal trade-off map):

An influential relation map can be drawn by mapping the dataset of ($TD+TR$, $TD-TR$) to show the directed influence of factors. The horizontal axis is represented by $TD+TR$. Higher $TD+TR$ suggests more interaction with other factors. The vertical axis is demonstrated by $TD-TR$. $TD-TR$ means the net influence effect that the factor devotes to the network. However, sometimes the diagram can become too complicated to show insightful information when there are too many factors and relations in the system. In this case, thresholds can be included to screen out the negligible factors and keep the factors whose strength of influence, including SE and TE, is greater than their corresponding thresholds. In the causal synergy/trade-off map of this study, we include the top five SDGs with the highest SE/TE. In this study, the thresholds of the strength of influence in the matrix T for causal synergy and trade-off maps are set as 0.10 and -0.013, respectively. The causal synergy map and causal trade-off map both consider two characteristics: (1) The direction between two goals, and (2) the strength of influence.

Step 6 (Group classification): The factor can be classified into five groups, that is, positive cause group, negative cause group, neutral group, positive effect group, and negative effect group. Positive $TD-TR$ indicates that factor F_i has a net influence on the other factors and belongs to the cause group. Based on the level of synergy effects and trade-off effects that are delivered, we can further divide them into the positive cause group and the negative cause group. Negative $TD-TR$ suggests that factor F_i is affected by other factors and can be classified into the effect group. Similarly, the effect group can be divided into the positive effect group and the negative effect group. If $TD-TR$ equals zero, the factor can be categorized into the neutral group.

$$\begin{cases} TD-TR>0 \text{ and } D^{+}\geq |D^{-}|:\ \text{Positive cause group,} \\ TD-TR>0 \text{ and } D^{+}<|D^{-}|:\ \text{Negative cause group,} \\ TD-TR<0 \text{ and } R^{+}\geq |R^{-}|:\ \text{Positive effect group,} \\ TD-TR<0 \text{ and } R^{+}<|R^{-}|:\ \text{Negative effect group,} \\ TD-TR=0:\ \text{Neutral group.} \end{cases} \tag{15}$$

Step 7 (Generating the weight of factors): in the traditional DEMATEL method, the weights are determined based on $TD+TR=[a_j]_{n\times 1}$ (Cebi, 2013; Si et al., 2018; Yazdani-Chamzini et al., 2014). However, this weight only focuses on the total amount of influence exerted or delivered by a factor without considering whether the influence is the synergy effect or trade-off effect. If a factor is a pure trade-off transmitter, the outcome brought by the improvement efforts of this factor can negatively affect other factors and may deteriorate the overall performance of the system. Therefore, an alternative method is presented to calculate the weight, which is based on the net influential effect indicator (NE). The main idea is that higher synergy effects and fewer trade-off effects (including as a transmitter and receiver) will result in a higher weight (importance). Let $i=j$ and $i,j\in\{1, 2, ..., n\}$. The NE can be obtained as follows:

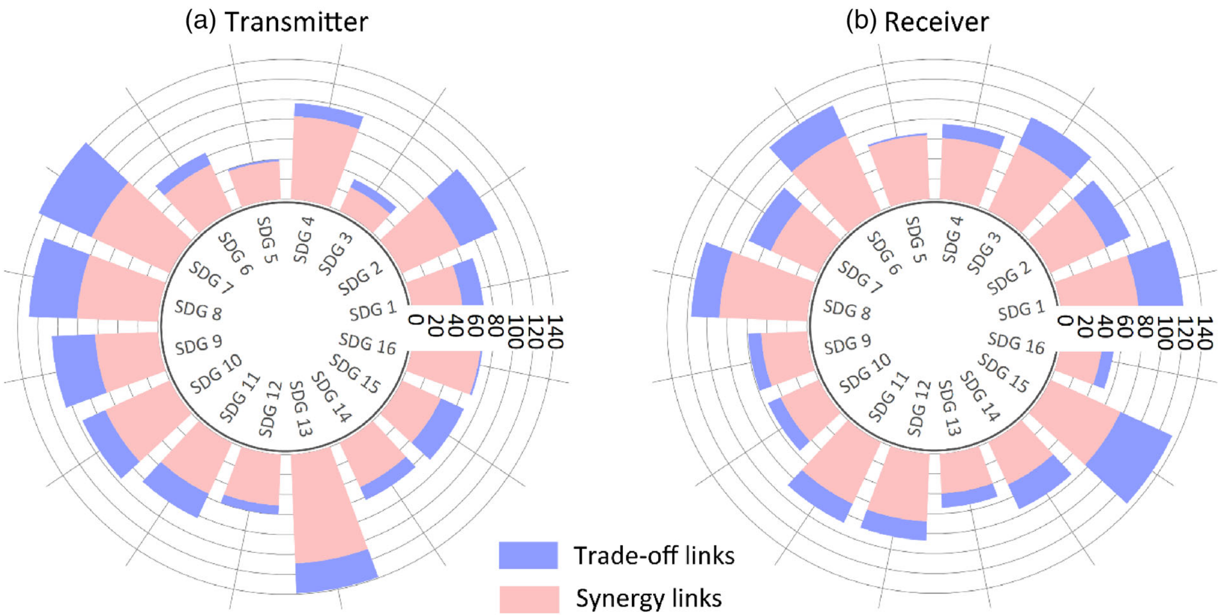

FIGURE 2 Number of direct synergy links and trade-off links of the sustainable development goals (SDGs). The SDGs as influence transmitters (a) and as influence receiver (b). A total of 150 targets under 16 SDGs are incorporated for interaction analysis. The number of synergy/trade-off link transmitted shown in (a) is equal to that of the synergy/trade-off links received shown in (b) [Colour figure can be viewed at wileyonlinelibrary.com]

$$NE = [ne_i] = \left[d_j^+\right]_{n\times 1} + \left[d_j^-\right]_{n\times 1} + \left[r_i^+\right]_{1\times n}^T + \left[r_i^-\right]_{1\times n}^T \tag{16}$$

Since NE can be positive and negative, it needs to be normalized to make it range from 0 to 1. We use the min-max method to standardize it. To avoid obtaining zero weight, the variable α is included in the min-max method and indicates the lowest value ne_i after normalization, which is determined by decision makers. In this study, we set the α at 0.1.

$$ne_i' = \alpha + \frac{ne_i - \min_{1\le i\le n}(ne_i)}{\max_{1\le i\le n}(ne_i) - \min_{1\le i\le n}(ne_i)} \times (1-\alpha) \tag{17}$$

The weight of each SDG can be obtained as follows:

$$W_i = \frac{ne_i'}{\sum_{i=1}^{n} ne_i'} \tag{18}$$

4 | RESULTS

4.1 | The direct synergy links and trade-off links across the SDGs

As shown in Figure 2, the progress of the SDGs can exert up to 989 synergy links with each other, which is around 2.6 times larger than that of the trade-off links (380 trade-off links). On average, the improvement of one goal has synergy links with 62 targets and trade-off links with 24 targets. These synergy links and trade-off links lay a theoretical foundation for nexus analysis that consider interactions among more sectors, such as water-food-energy-climate nexus (SDG 6-SDG 2-SDG 7-SDG 13), energy-poverty-climate nexus (SDG 7-SDG 1-SDG 13), and food-energy-water-health nexus (SDG 2-SDG 7-SDG 6-SDG 3). These direct synergy links and trade-off links of the SDGs are based on past observations around the world, suggesting we considered relatively comprehensive situations. However, these links may be weakened or even do not exist if the construction of interaction network across SDGs are based on specific context. To be specific, the SDG interaction results of case study in Europe can be different from that in Asia, and even within the same region, the linkage results may change with sustainable transformation by choosing different measures to achieve SDGs (Ladha et al., 2020).

The improvement of SDG 13 (Climate change) exhibits the broadest range of synergy links with the targets of the remaining goals, numbering 109, followed by SDG 7 (Affordable and clean energy; 86 synergy links) and SDG 4 (Quality education; 83 synergy links; Figure 2). SDG 13 (Climate change) can contribute to plenty of sectors and individuals of a society by capitalizing on co-benefits, such as poverty reduction, agriculture production, clean water and sanitation services, and energy systems. Although there are many synergy links between different SDGs, a close eye should be kept to guarantee that improvements achieved in some SDGs are not at the cost of the deterioration of other SDGs. Achieving SDG 8 (Decent work and economic growth) and SDG 9 (Industry, innovation, and infrastructure) will negatively affect a relatively large number of targets of other goals, numbering 48 and 43, respectively (Figure 2a). Most of the trade-off links

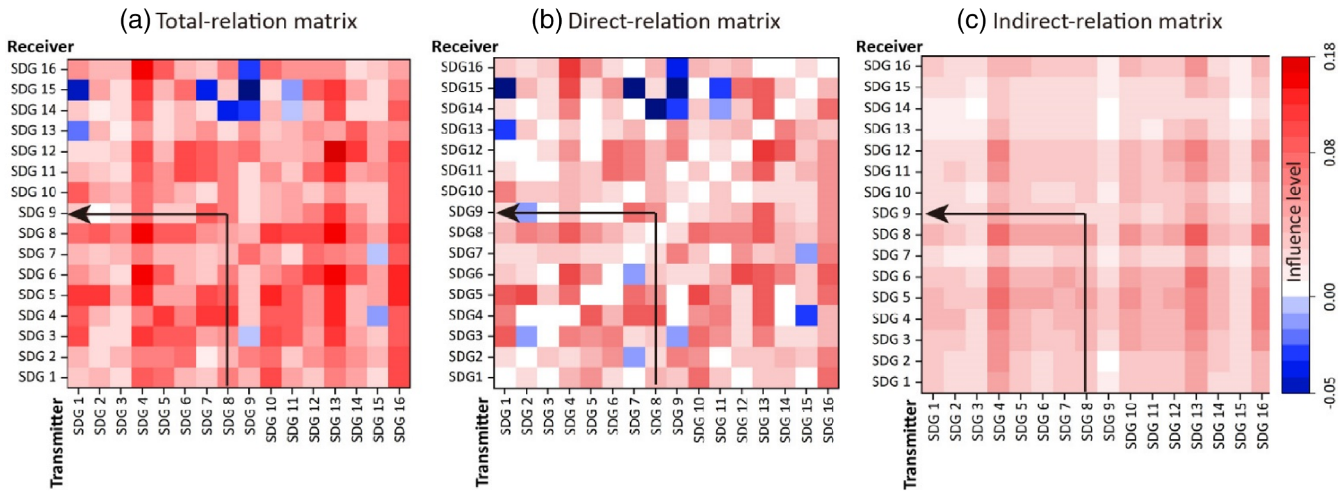

FIGURE 3 The causal relationship matrix of the sustainable development goals. The total-relation matrix (a) is the summation of direct-relation-matrix (b) and indirect-relation matrix (c). The direct influence reflects the synergy and trade-off links shown in Figure 2 [Colour figure can be viewed at wileyonlinelibrary.com]

are related to ecosystems and natural resources, such as SDG 15 (Life on land), SDG 14 (Life below water), SDG 7 (Affordable and clean energy), and SDG 6 (Clean water and sanitation; Figure S2). SDG 15 (Life on land) receives the largest number of trade-off links from SDG 8 (Decent work and economic growth) and SDG 9 (Industry, innovation, and infrastructure), numbering 10 and 8, respectively (Figure S2). It can be interpreted that the natural environment is the basis of economic activities, providing raw materials (e.g., timber, fishery resources, and water) for human needs to generate goods and services. However, consuming environmental resources to meet the human needs in an unsustainable way can negatively affect terrestrial ecosystems.

4.2 | The indirect effects across the SDGs

The total-relation matrix based on the proposed model is shown in Figure 3a and Table S1, which is the summation of the direct and indirect influence among the SDGs. The total-relation matrix, direct-relation matrix, and indirect-relation matrix are a kind of causal relationship matrix. Causal relationship suggests the influence is directional, which is represented by the black arrows in Figure 3. The horizontal axis and vertical axis indicate the influence transmitter and influence receiver, respectively. Darker color in Figure 3 means stronger strength of interactions. The indirect influence suggests that there will be at least one medium that delivers the influence between two goals. For instance, the achievement of SDG 7 (affordable and clean energy) can help to mitigate climate change by reducing CO_2 emissions (Target 13.2; Shan et al., 2018; Xiao et al., 2019), while climate change poses major stress for terrestrial ecosystems through the deglaciation of mountain systems, increased desertification, habitat loss, and other climate-related factors (Target 15.1–15.5; Nerini et al., 2019). Therefore, the achievement of SDG 7 (Affordable and clean energy) can have a positive impact on Target 13.2 directly, while SDG 7(Affordable and clean energy) exerts a negative impact on Target 15.1–15.6 in an indirect way. SDG 13 (Climate change) is the largest indirect synergy effect transmitter, followed by SDG 4 (Quality education) and SDG 16 (Peace, justice, and strong institutions; Figure 3c).

The neglect of indirect effects can lead to an inaccurate evaluation of interactions among the SDGs. Specifically, when considering both direct and indirect interactions, the goal with the highest synergy effects as a transmitter is SDG 13 (Climate change), followed by SDG 4 (Quality education) and SDG 16 (Peace, justice, and strong institutions; Figure 3a). This result is different from the rank when only considering the direct synergy across the SDGs shown in Figure 2 (SDG 13 > SDG 7 > SDG 4).

4.3 | The components of total influence of each goal

The components of the total influence received for each goal shown in Figure 3a can be decomposed into two parts, that is the synergy receiver (R^+), and the trade-off receiver (R^-) (Figure 4a). Even though the trade-off effects exist in all SDGs, the share of synergy receiver component (R^+) of a goal dominates the total influence received ($R^+ + R^-$), on average, taking up to 98.33% (Figure 4a, Table S3). This suggests that interactions can significantly facilitate the achievement of the 2030 Agenda by unlocking the full interaction potential. Since the influence receiver and transmitter are two faces of the same coin, the same as the synergy receiver component, the share for synergy transmitter component (D^+) also accounts for 98.33% of the total influence exerted ($D^+ + D^-$; Figure 4a). For SDG 9 (Industry, innovation, and infrastructure), the influence level of $D+$, $D-$, $R+$, and $R-$ is 0.45, 0.10, 0.77, and 0.00, respectively (Figure 4a; Table S3).

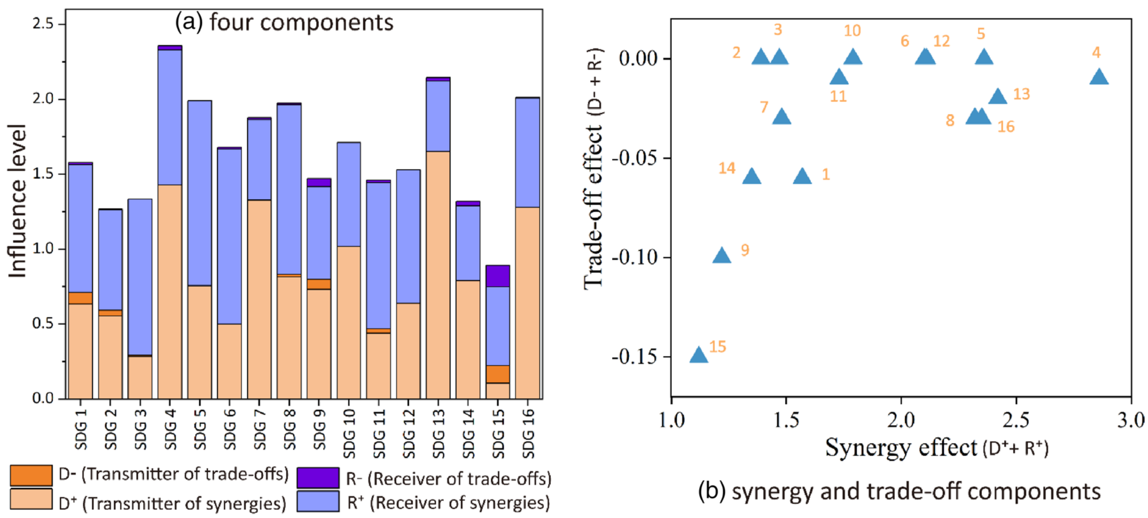

FIGURE 4 Influence components of the sustainable development goals (SDGs). The total influence of an SDG can be divided into four components, that is, the transmitter of trade-offs, the transmitter of synergies, the receiver of trade-offs, and the receiver of synergies (a). Synergy effects are the summation of transmitter of synergy and receiver of synergy, while trade-off effects are the summation of transmitter of trade-offs and receiver of trade-offs (b). In diagram (B), the number beside the triangle indicates the corresponding SDG (e.g., 1 means SDG 1) [Colour figure can be viewed at wileyonlinelibrary.com]

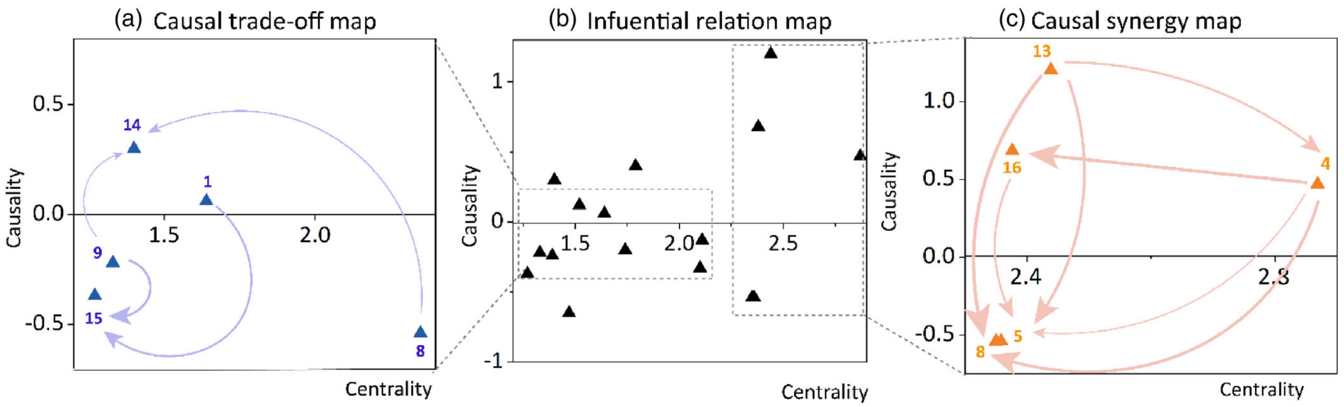

FIGURE 5 The influential relation map (b), causal trade-off map (a), and causal synergy map (c) of the sustainable development goals (SDGs). The thickness of the arrow in diagram (a) and (c) indicates the strength of influence from a SDG on another SDG. Thicker arrows mean stronger influence. Blue arrows in (a) and red arrows in (c) indicate trade-off linkages and synergy linkages, respectively. Causality and centrality indicate TD − TR and TD + TR, respectively. The number beside the triangle indicates the corresponding SDG (e.g., 1 means SDG 1) [Colour figure can be viewed at wileyonlinelibrary.com]

Meeting SDG 5 (Gender equality), SDG 6 (Clean water and sanitation), and SDG 8 (Decent work and economic growth) in isolation can underestimate their performance since they can receive significant synergy effects from other SDGs. These three SDGs receive the largest amount of synergy effects from other SDGs, with $R^+ = 1.45$, $R^+ = 1.22$, and $R^+ = 1.45$ (Figure 4a, Table S3), respectively. In comparison, SDG 15 (Life on land) is the largest trade-off receiver, with $R^- = 0.14$, followed by SDG 14 (Life below water; $R^- = 0.06$) (Figure 4a, Table S3). The inherent tensions and trade-offs received by these three goals can undermine their achievement. Notice that SDG 15 (Life on land) is located in the left lower corner in Figure 4b, indicating that this goal has the smallest synergy effects and the largest trade-off effects. For example, protecting terrestrial ecosystems, halting deforestation, and preserving biodiversity (SDG 15: Life on land) could potentially conflict with the expansion of renewable energy sources (SDG 7: Affordable and clean energy), especially limiting the use of hydropower on a large scale. Policymakers should keep a close eye on SDG 15 (Life on land) to avoid undermining the achievement of the 2030 Agenda through its trade-off linkages. Some studies have found that trade-off effects can be turned into synergy effects by adopting proper measures (Kroll et al., 2019). For instance, sustainable land and water management can resolve some trade-offs on SDG 7 by promoting bioenergy production. Also, compared with other SDGs, maximizing the benefits of the whole sustainable system using the synergy linkage with SDG 15 (Life on land) can be relatively limited.

Goal	Description	Group classificaion					Weight
		Positive cause	Negative	Positive effect	Negative	Neutral	
SDG 1	No poverty			√			0.044
SDG 2	Zero hunger			√			0.037
SDG 3	Good health and well-being			√			0.042
SDG 4	Quality education	√					0.123
SDG 5	Gender equality			√			0.094
SDG 6	Clean water and sanitation			√			0.079
SDG 7	Affordable and clean energy	√					0.040
SDG 8	Decent work and economic growth			√			0.090
SDG 9	Industry, innovation, and infrastructure	√					0.021
SDG 10	Reduced inequalities	√					0.061
SDG 11	Sustainable cities and communities			√			0.057
SDG 12	Responsible consumption and production			√			0.079
SDG 13	Climate change	√					0.097
SDG 14	Life below water	√					0.031
SDG 15	Life on land			√			0.012
SDG 16	Peace, justice, and strong institutions	√					0.092

FIGURE 6 Group classification and weight of the sustainable development goals. The goals can be classified into five groups, that is, positive cause group, negative cause group, neutral group, positive effect group, and negative effect group. If the degree of causality is positive, the goal has a net influence on the other goals and can be categorized in the cause group; if the degree of causality is negative, the goal is being influenced by the other goals overall and should be classified in the effect group. The summation of the weight equals 1 [Colour figure can be viewed at wileyonlinelibrary.com]

4.4 | The causal map of key interactive goals

The influential relation diagram of SDGs is shown in Figure 5b, where the TD + TR means the centrality of the goal and TD-TR reflects the causality. There are seven SDGs whose causality degrees are positive (SDGs 1, 4, 7, 10, 13, 14, and 16), indicating that these seven SDGs tend to deliver influence on others instead of being influence receivers (Figure 5b, Table S3). For the other SDGs with a degree of negative causality, they are easily affected by other SDGs. Among them, the degree of causality of SDG 3 (Good health and well-being) is the lowest (−0.65), followed by SDG 5 (Gender equality; −0.54) and SDG 8 (Decent work and economic growth; −0.54) (Figure 5b, Table S3).

A larger degree of centrality suggests that the influence with other goals is stronger. The goals with the highest degree of centrality are SDG 4 (Quality education) and SDG 13 (Climate change; Figure 5b). These two goals also have the largest total synergy effects (Figure 5c). A close eye on the synergies of these five goals is important, which can help to create positive synergies, and further achieve the SDGs effectively. We further draw the causal relation diagram to see the interactions among the top five goals with the largest total synergy effects, as shown in Figure 5c. SDG 4 (Quality education) exerts a strong positive influence on SDG 16 (Peace, justice, and strong institutions), indicating that the achievement of SDG 4 (Quality education) can contribute to improving SDG 16 through interactions (Figure 5c). Also, SDG 4 (Quality education) is located in the upper right corner of Figure 4c, suggesting that SDG 4 (Quality education) has large synergy effects with other goals, and at the same time, the trade-off linkage is relatively small. It can be interpreted that education is the center of a society's growth and progress because well-educated people can significantly contribute to a harmonious family and a progressive society in a variety of aspects and fields (Friedman et al., 2020). Policymakers can create positive synergies based on these positive interactions among the SDGs and achieve the SDGs effectively.

The causal trade-off map of the top five goals with the largest total trade-off effects is shown in Figure 5a. For better demonstration, the causal trade-off map only includes the top five influential SDGs (SDG 1, 8, 9, 14, and 15) with highest total trade-off effects (Figure 5a). SDG 15 (Life on land) receives a large amount of trade-off from SDG 9 (Industry, innovation, and infrastructure) and SDG 1 (No poverty; Figure 5a). This suggests that the achievement of SDG 9 and SDG 1 can negatively affect the progress of other goals (e.g., SDG 15) and may deteriorate the overall performance of the system.

4.5 | Weight and group classification of the SDGs

Although all SDGs should be equally addressed by 2030 as mentioned by the United Nations, the weight/importance of each goal is different to tap into the full potential of the efforts made in achieving one goal through interactions. The weights of each goal can be found in

Figure 6, which can be applied to the multi-criteria decision-making analysis. The aggregation of the weights of these 16 SDGs is equal to 1. Higher synergy effects and fewer trade-off effects will result in a higher weight (importance) assigned to this goal. The weight of SDG 4 (Quality education) is the largest, at 0.123, followed by SDG 13 (0.097), SDG 5 (0.094), and SDG 16 (0.092), while the top five goals with the lowest weight are SDG 15 (0.012), SDG 9 (0.021), SDG 14 (0.031), SDG 2 (0.037), and SDG 7 (0.040; Figure 6). The weight can be a reference for the policymakers to put a premium on when moving toward the 2030 Agenda and tap into the full potential of the efforts made in achieving one goal through interactions. As such, SDG 4 and SDG 13 are the top priority to unlock these interaction potentials through maximizing the synergies and minimizing the trade-offs.

SDGs 4, 7, 9, 10, 13, 14, and 16 belong to the positive cause group, indicating that they tend to exert positive impacts on other goals and should be the top priority of the improvement management (Figure 6). Eight goals (SDGs 1, 2, 3, 5, 6, 8, 11, 12, 15) can be classified into positive effect groups, suggesting that the goals are more likely to receive synergy effects from other goals (Figure 6). These SDGs can be improved in an indirect way, such as enhancing the synergy effects and reducing trade-off effects from the goals in the cause group. None of the goals are categorized in the negative cause group or negative effect group, showing that the synergy effects are larger than trade-off effects for all SDGs. Also, none of the goals belong to neutral group, suggesting all goals are dependent of each other.

5 | DISCUSSION

The direct synergy and trade-off database of the SDGs at the target level we constructed can be a reference for interaction-related studies and cooperation of multiple disciplines and sectors. Also, the proposed method which can incorporate indirect synergies and trade-offs is not limited to the SDGs-related study but can be applied to broader multi-criteria decision-making fields. Our evidence has shown that none of the goals are independent of the others but are significantly indivisible and interrelated. The realization of one goal, to some extent, depends on the solution of other related problems, and that action in one area will positively or negatively affect outcomes in others. Synergy effects between different goals were found to outweigh the trade-off effects, which is consistent with existing studies (Pham-Truffert et al., 2020; Pradhan et al., 2017; Warchold et al., 2021), indicating that the achievement of the 2030 Agenda can be facilitated by unlocking the interaction potential. This study suggested that achieving SDG 4 (Quality education) and SDG 13 (Climate change) can significantly facilitate the achievement of the 2030 Agenda since these two SDGs can generate the strongest synergy effects on other SDGs. At the same time, attention should be paid to the main trade-off transmitters, such as SDG 15 (Life on land) and SDG 9 (Industry, innovation, and infrastructure), which can negatively affect the progress of other goals and may deteriorate the overall performance of the system. Interaction analysis across SDGs has been evaluated in many studies in recent years; however, there is no affirmative conclusion about which SDGs should be the top priority to facilitate the achievement through interaction. For example, Pradhan et al. (2017) suggested that SDG 1 (No poverty) and SDG 12 (Responsible consumption and production) has synergetic and trade-off relationship with most of the other SDGs, respectively (Pradhan et al., 2017). However, this study used Spearman correlation method to analyze their correlation relationship and did not take the indirect interaction across SDGs into consideration (Pradhan et al., 2017). Anderson et al. (2022) suggested that efforts toward SDGs 5 (Gender Equality) and 17 (Partnerships for the Goals) could facilitate SDG progress, whereas SDGs 10 (Reduced Inequalities) and 16 (Peace, Justice and Strong Institutions) could generate significant trade-off effects (Anderson et al., 2022). This study provided important information about SDG interaction by taking indirect interaction into consideration; however, this study quantifies a relatively small target pairs with causal relationship (97 positive pairs and 34 negative pairs). In other words, our findings that considered both direct and indirect interactions and covered a relatively comprehensive SDG interaction with causal relationship are an important complement to the SDG interaction analysis.

The achievement of the 2030 Agenda requires integrated strategies and collaboration of all sectors in a society instead of simply ticking off targets one be one. Career development and academic research generally focus on specific subject matter, which is often unconnected due to the division of labor and disciplinary differences, and relatively limited research has been conducted across them. The interactions among the SDGs show that we should systematically evaluate synergies and trade-offs across sectors and disciplines. This is challenging since their relationship is complex and rich. Dealing with this challenge requires a variety of knowledge communities to jointly address the most pressing sustainable development challenges of the world coherently and synergistically. It is significant in this context of the SDGs to acknowledge and solve ingrained cultures and norms that maintain the beneficial exchange of information and ideas. Some cross-cutting topics such as water-energy nexus, food-water nexus, and energy-poverty-climate nexus are starting to draw our attention, but these do not yet predominate enough. The increasing body of studies on the interrelationship of the SDGs across disciplines is encouraging but remains limited to relatively small number of research groups. It is still necessary to expand the current research breadth to incorporate more sectors and disciplines. For that to happen, large research institutes are suggested to dedicate some time and effort to identifying how their focal research areas interact and promote interdisciplinary programs and collaborations.

Apart from expanding the breadth across disciplines and sectors, depth of knowledge is an indispensable step to be strengthened in achieving the 2030 Agenda. We need to address all targets described in the 2030 Agenda, but more importantly, we need to prioritize efficient and effective sustainability interventions across societies, economies, and environments. As such, the deep understanding of participants in these prioritized targets and the SDGs is significant, which can help us to effectively understand which discipline/sectors could become partners and which ones we need to negotiate with.

The deep study and practice will further help policymakers to design coherent policies and strategies and unlock the interaction potential of the SDGs effectively.

6 | CONCLUSIONS

This study made a methodological contribution by proposing a plus-minus DEMATEL, which can consider not only the direct synergies and trade-offs but the indirect ones. Then, based on this proposed method, we navigate the complicated network across the SDGs considering both direct and indirect interactions, find out the key interactive ones with a visually directed graph, obtain the weights of each SDG, and define the best governance structures to capitalize on synergies and minimize trade-offs.

The study finds that, on an average, when incorporating both direct and indirect interactions, the share of synergy effect dominates the influence, taking up to 98.33%, suggesting that the achievement of the 2030 Agenda can be facilitated through interactions. The goal with the highest synergy effects as a transmitter is SDG 13 (Climate change), followed by SDG 4 (Quality education) and SDG 16 (Peace, justice, and strong institutions).

Moreover, although all SDGs should be equally addressed by 2030 as mentioned by the United Nations, the weight of each goal is different to unlock the full potential of the efforts made in achieving one goal through interactions. The weight of SDG 4 (Quality education) is the largest, at 0.123, followed by SDG 13 (Climate change; 0.097) and SDG 5 (Gender equality; 0.094).

Our empirical results have several significant policy implications. First, the United Nation's "Decade of Action" of SDGs calls for accelerating sustainable solutions to all the world's biggest challenges by 2030. Our interdisciplinary analysis across economic growth, social inclusion, and environmental protection provides a science-driven reference for the United Nation's Member States around the world to facilitate this achievement by maximizing the synergies and minimize the trade-offs. Additionally, this study can be a basic not only for science-policy conversations of multiple disciplines and sectors but lay a theoretical foundation for nexus analysis among more sectors (e.g., water-food-energy-climate nexus, energy-poverty-climate nexus, and food-energy-water-health nexus).

7 | LIMITATIONS AND FUTURE WORK

There are several limitations of the analysis about the interlinkages across the SDG targets. First, the nature of some SDG interactions (synergies and trade-offs) is based on specific context, such as period selection of applied measures, income level of a region, geographical location, and population groups (Warchold et al., 2021). Some studies have pointed out that some trade-offs can be transformed into synergies and vice versa (Kroll et al., 2019). Future studies should evaluate the spatial–temporal variations in SDG interactions based on the specific context (e.g., a case study in Europe). Second, the linkage dataset only considers the nature of the interaction (neutral, synergies, and trade-offs) based on existing studies, suggesting the aggregating of the number of interaction linkages cannot fully reflect causal relations among SDG. In the future, apart from the number of interaction linkages, we can also take the strength of the interaction (small or large impacts) into consideration to construct a more comprehensive interaction network, which can more accurately reflect the insights of the interaction across SDGs. The strength can refer to the seven-point scale proposed by Nilsson et al. (2016) based on the consensus-based expert elicitation and published studies.

AUTHOR CONTRIBUTIONS

Jingzheng Ren: Supervision, resources, data curation, and writing-review and editing. **Huijuan Xiao:** Conceptualization, data curation, formal analysis, methodology, writing-original draft. **Yue Liu:** Data curation, writing-review and editing.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The code for the plus-minus decision-making trial and evaluation laboratory model can be accessed at supplemental information. The direct-relation synergy matrix and direct-relation trade-off matrix can be accessed at https://doi.org/10.6084/m9.figshare.16698265.v1.

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SUPPORTING INFORMATION

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