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Interactions in water-energy-food security nexus: A case study of South Korea

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With the exponential increase in the demand for water, energy, and food (WEF), WEF security is being threatened. To address this issue, the nexus approach, which explores interactions among different WEF sectors as an integrated system, can distinguish between different influencing indicators of WEF security. However, studies on the interactions between WEF sectors in South Korea are few, consequently challenging WEF security, and in the field of social science, WEF security nexus research using a quantitative approach is lacking. This study discusses the interactions composed of synergies and trade-offs between WEF sectors in South Korea through Spearman's rank correlation and network analyses using secondary data at the national level. The results show that the interaction between energy or energy-related sectors was highest; specifically, increasing the proportion of renewable energy utilization improved WEF security. In the water and food sectors, water infrastructure management and value-added management of agriculture showed the most interactions, respectively. The findings demonstrate that WEF security is an interconnected rather than an independent system, and WEF security improves efficiently when preferentially upgrading indicators with many interactions. The study provides important guidelines to prioritize policies to implement sustainable resource management systems.

KEYWORDS

water-energy-food nexus, synergies, trade-offs, resource management, water security, energy security, food security, WEF security

Introduction

Water, energy, and food (WEF) are essential resources necessary for human survival (Adnan, 2013; Bizikova et al., 2013), and their demand is expected to increase worldwide by 80, 55, and 60%, respectively, in 2050 (Flammini et al., 2014) due to factors such as industrialization, urbanization, population explosion, and economic growth (Hoff, 2011). Consequently, the supply of corresponding resources can be disrupted, which in turn can diminish resource security (World Economic Forum, 2011). The concept of the WEF nexus, which is a holistic framework used to analyze the trade-offs and synergies between water, energy, and food, has emerged to address the problem of WEF security (Albrecht et al., 2018; Terrapon-Pfaff et al., 2018). As the three components of the

nexus are inextricably linked, they should be considered integratively (Brears, 2018). For example, food production consumes ~70 and 30% of total global freshwater and energy worldwide, respectively (FAO, 2017). Moreover, bio-crops are not only food resources, but can also be used as a renewable bioenergy source (International Renewable Energy Agency, 2019). Furthermore, the water sector, involving wastewater transfer, treatment, re-use, desalination, distribution, and supply, consumes ~4% of the world's electricity, whereas primary energy production and power generation consume ~10% of the world's water resources (International Energy Agency, 2016).

The WEF nexus approach explores interconnections among different WEF sectors that can be generally regarded as synergies, wherein advances in one sector promote advances in another, and trade-offs, in which advances in one sector hinder advances in another (Putra et al., 2020). Synergies enhance WEF security, whereas trade-offs undermine WEF security (Cai et al., 2018). A cross-sectoral nexus approach to WEF sectors provides an opportunity to fulfill positive synergies and effectively manage trade-offs (Hoff, 2011). This approach could help to achieve the sustainable development goals (SDGs) of the United Nations because SDGs 2 (Zero hunger), 6 (Clean Water and Sanitation), and 7 (Affordable and Clean Energy) are closely related to water, energy, and food, respectively (Liu et al., 2018). Therefore, understanding the interactions among the WEF sectors, maximizing synergies, and minimizing trade-offs, could improve the overall WEF security while achieving SDGs (Karnib, 2018; Stephan et al., 2018; Terrapon-Pfaff et al., 2018).

Previous studies on the WEF security nexus have focused on global (Ringle et al., 2016), transboundary river basin (Amjath-Babu et al., 2019), local (Mroue et al., 2019), and regional (Mahlknecht et al., 2020; Saidmamatov et al., 2020) approaches. Several studies have been conducted on WEF security since the Bon 2011 Nexus Conference (Leck et al., 2015; Endo et al., 2017). However, according to Albrecht et al. (2018), quantitative research on the relationship among WEF sectors are limited at the national scale. Besides, in nexus-related research fields, the environmental science approach is dominant while the social science approach is insufficient (Newell et al., 2019).

South Korea does not have abundant natural resources and is thus facing difficulties to ensure WEF security. First, its renewable water resources per capita (1,453 m³) rank 129 among 153 countries (Ministry of Environment Korea Water Resources Corporation, 2020). Generally, managing water resources is easy and feasible if precipitation is uniformly distributed seasonally; however, in South Korea, precipitation is concentrated in summer. Second, because of the low abundance of natural resources, the country highly depends on imported natural resources for energy production that account for 94% (Korea Energy Economics Institute,

2019). Lastly, the food self-sufficiency rate in South Korea is only 23%, with major dependency on imports for food resources (Korea Rural Economic Institute, 2019a). Based on these factors, comprehensively investigating the WEF security nexus can help achieve sustainable resource management. Furthermore, understanding the interactions among the WEF indicators can not only provide a broader perspective of the relationship among the WEF sectors, but can also help to establish a priority implementation strategy to address WEF nexus security challenges (Huang et al., 2020). Wicaksono and Kang (2019) assessed the feedback analysis results and calculated the reliability index of resources resulting from energy policy changes in South Korea by examining the interlinkages between WEF sectors. Moreover, Wicaksono et al. (2019) proposed an optimization approach to maximize the reliability index of WEF security under plausible drought scenarios, and Lee et al. (2020) analyzed the food-related interconnections in the WEF nexus under different scenarios of climate change and changes in irrigation management. Despite numerous studies and unpredictable resource security, there are still few study cases of the WEF nexus targeting South Korea; additionally, explorations of the interactions between WEF security nexus indicators in South Korea are absent.

To fill these research gaps, this study aimed to perform a quantitative analysis of synergies and trade-offs identified between the WEF security indicators in South Korea using Spearman's rank correlation analysis and network analysis. The specific objectives were: (1) to identify the interactions in WEF security indicators for South Korea, (2) to analyze the most influential indicators in the WEF security nexus, and (3) to provide policy priorities for an effective resource management. The results can facilitate the identification of indicators, whose improvements need to be prioritized by sector, to ensure WEF security. The systematic framework on the assessment of WEF interactions proposed in this study makes a fundamental contribution to policy implementation, which can ensure the effective management of water, energy, and food resources.

Materials and methods

Materials

To identify the indicators influencing the WEF security nexus, the indicators in this study were selected based on the criteria defined in previous studies. Simpson et al. (2020) developed a composite indicator that can effectively measure the WEF nexus using a method developed by the European Commission. Flammini et al. (2014) proposed comprehensive indices for determining the interactions among WEF sectors. Moreover, Bizikova et al. (2013) defined utilization, access,

and availability as core indicators of WEF security and further categorized them. For SDGs indicators, SDGs 2 (Zero hunger), 6 (Clean Water and Sanitation), and 7 (Affordable and Clean Energy) were considered by Liu et al. (2018) and Stephan et al. (2018). Referring to these studies, 48 indicators, including 16 indicators each for water, energy, and food, were selected in the present study (Table 1). These indicators considered the availability, accessibility, affordability, and productivity factors of WEF security in South Korea. Data for the selected 48 indicators were obtained for 2004–2018 from the SDG database (UN, 2021), International Energy Agency (2021), FAOSTAT (2021), World Bank (2021), Organization for Economic Cooperation and Development (2021), and the statistics databases of the South Korean government (Korea Energy Economics Institute, 2019; Ministry of Agriculture, Food and Rural Affairs of South Korea, 2020; Ministry of Environment of South Korea, 2020, 2021; GIMS, 2021; Korean Statistical Information Service, 2021). The research approach followed in this study was similar to that of Putra et al. (2020), who analyzed the interactions among the WEF sectors from five South Asian countries; however, in the present study, comparatively more indicators were considered with the focus only on one country, that is, South Korea.

Investigation of interactions

This study investigated the synergies and trade-offs among the WEF sectors mathematically, following the methodological approach suggested by Pradhan et al. (2017), who analyzed the interactions among SDGs by analyzing the official SDG indicator data of 227 countries using Spearman's rank correlation. This approach was also used by Putra et al. (2020) and Hao et al. (2022) to investigate interactions among different WEF security indicators. The author analyzed the correlations among the WEF security indicators as synergies (positive) and trade-offs (negative) based on Pradhan et al. (2017). All indicator values were re-coded consistently to advance WEF security and avoid false correlations. A positive sign was assigned to indicators that improved the WEF security when the indicator value increased, and a negative sign was assigned to indicators that reduced the WEF security when the indicator value increased. For example, a positive sign was assigned to “W3 (water use efficiency)” because an increase in the indicator improved water security; moreover, a negative sign was assigned to “F12 (non-arable land)” because an increase in the indicator decreased food security.

Spearman's rank correlation analysis, for which the coefficient is derived using the ranks of two values instead of the actual data values (Spearman, 1904), was used to identify the correlations between paired indicator values. The correlation coefficient was calculated using the

TABLE 1 Indicators selected to investigate the water, energy, and food (WEF) security nexus of South Korea.

ID	Description	Sign	Source
W1	Safe drinking water	1	SDG ¹ 6.1.1
W2	Safe sanitation water	1	SDG 6.2.1
W3	Water use efficiency	1	SDG 6.4.1
W4	Level of water stress	−1	SDG 6.4.2
W5	Lake and river area	1	SDG 6.6.1
W6	Water usage per capita	−1	MOE ²
W7	Agricultural water consumption	−1	MOE
W8	Industrial water consumption	1	MOE
W9	Municipal water consumption	1	MOE
W10	Annual precipitation	1	KOSIS ³
W11	Ground water for agriculture	−1	GIMS ⁴
W12	Water supply service fee	−1	KOSIS
W13	Water supply service rate	1	KOSIS
W14	Water withdrawals	−1	OECD ⁵
W15	Wastewater treatment	1	OECD
W16	Sewerage supply rate	1	KOSIS
E1	Access to clean fuels for cooking	1	SDG 7.1.2
E2	Renewable energy consumption	1	SDG 7.2.1
E3	Energy intensity	−1	SDG 7.3.1
E4	Emission from energy sector	−1	MOE
E5	Energy usage in agriculture	1	IEA ⁶
E6	Electricity consumption per capita	1	IEA
E7	Electricity generation by solar	1	IEA
E8	Electricity generation by wind	1	IEA
E9	Electricity generation by biofuels	1	IEA
E10	Electricity generation by waste (renewable)	1	IEA
E11	Electricity generation by coal	−1	IEA
E12	Electricity generation by oil	−1	IEA
E13	Electricity generation by nature gas	−1	IEA
E14	Electricity generation by nuclear	−1	IEA
E15	Energy imports	−1	KEEI ⁷
E16	Budget for low-carbon energy technologies	1	IEA
F1	Stunting children	−1	SDG 2.2.1
F2	Overweight children	−1	SDG 2.2.2
F3	Value-added management of agriculture	1	SDG 2.a.1
F4	Emission from agriculture sector	−1	MOE

(Continued)

TABLE 1 Continued

ID	Description	Sign	Source
F5	Food production index	1	FAOSTAT ⁸⁾
F6	Cereal production	1	KOSIS
F7	Arable land	1	World Bank
F8	Cereal self-sufficiency rate	1	MAFRA ⁹⁾
F9	Fertilizer usage	1	FAOSTAT
F10	Crops and livestock products import	-1	FAOSTAT
F11	Consumer food price index	-1	OECD
F12	Non-arable land	1	MAFRA
F13	Agricultural productivity	1	KOSIS
F14	Meat consumption	1	OECD
F15	Food supply	1	KOSIS
F16	Rail line density	1	FAOSTAT

1) SDG, Sustainable Development Goal; 2) MOE, Ministry of Environment of South Korea; 3) KOSIS, Korean Statistical Information Service; 4) GIMS, National Groundwater Information Management & Service Center; 5) OECD, Organization for Economic Cooperation and Development; 6) IEA, International Energy Agency; 7) KEEL, Korea Energy Economics Institute; 8) FAOSTAT, Food and Agriculture Organization Corporate Statistical Database; 9) MAFRA, Ministry of Agriculture, Food and Rural Affairs of South Korea.

following equation:

$$r_s = 1 - \frac{6 \sum d^2}{n(n^2 - 1)}$$

where r_s is Spearman's rank correlation coefficient, d is the difference in ranks between the paired items, and n is the number of pairs of observations.

Similar to Pearson's correlation coefficient, the correlation coefficient ranges from -1 to 1 , with a value of 1 indicating a strong positive correlation, -1 indicating a strong negative correlation, and 0 indicating no correlation (Myers et al., 2013). However, unlike Pearson's correlation analysis, Spearman's rank correlation can identify the correlations for non-linear relationships and can be applied to discrete and ordered data if the data can be ranked (Hauke and Kossowski, 2011). Moreover, Spearman's rank correlation is used as an alternative to the Pearson correlation coefficient since it is less sensitive to outliers due to the utilization of ranks rather than actual data values in the calculation and can capture the strength of monotonic relationships (Conover, 1999).

According to previous studies (Pradhan et al., 2017; Kroll et al., 2019; Putra et al., 2020; Ronzon and Sanjuán, 2020; Hao et al., 2022), a Spearman's rank correlation coefficient value of 0.6 or higher indicated a "synergy," whereas a value of -0.6 or lower indicated a "trade-off." Moreover, if the value ranged between -0.6 and 0.6 , the correlation was interpreted as "unclassified" to avoid over-analysis (Hauke and Kossowski, 2011). Furthermore, only statistically significant correlations, that is, with $p < 0.05$, were considered. The open-source software Jamovi was used

to perform Spearman's rank correlation analysis (The Jamovi Project, 2021).

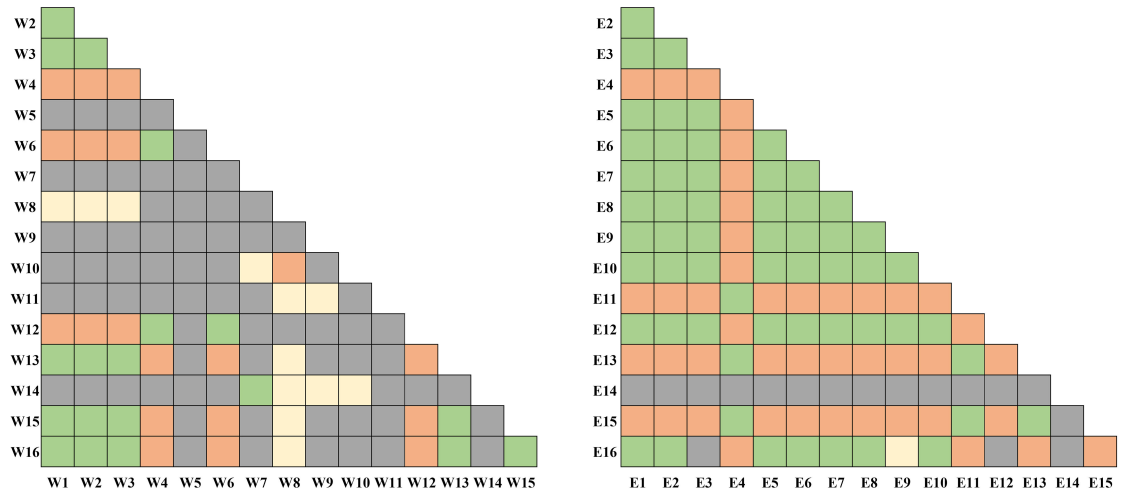
Network analysis

To discern the most influential indicators of the WEF security nexus for South Korea, network analysis was used, which has been utilized previously to analyze the most influential indicators and interactions between objects (Stein et al., 2014; Kurian et al., 2018; Weitz et al., 2018; Yeh et al., 2019; Mahjabin et al., 2020; Putra et al., 2020; An et al., 2021; Swain and Ranganathan, 2021). Network analysis is a well-developed methodology that provides various tools to analyze the relationships between objects and the patterns and interpretations of such relationships (Wasserman and Faust, 1994). The network generally comprises nodes representing objects and edges that interconnect the pairs of nodes. In this study, the selected 48 indicators were interpreted as nodes, and the interactions between each pair of indicators, analyzed through Spearman's rank correlation analysis, were interpreted as edges. Thus, the interactions between WEF security indicators could be visualized. The open-source software Gephi was used to visualize the network (Bastian et al., 2009).

Results

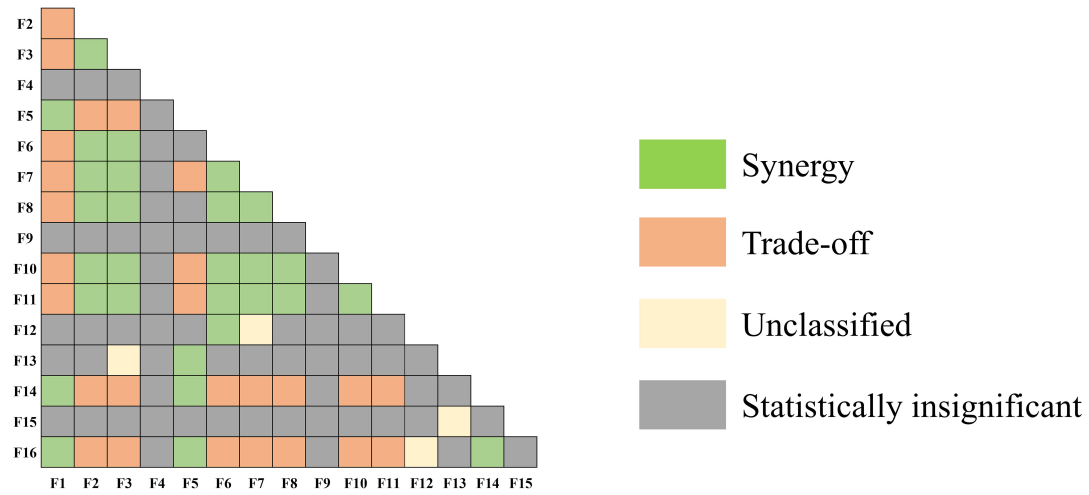
Interactions within WEF security indicators

Figures 1, 2 show the results of analyzing the interaction between WEF security using Spearman's rank correlation analysis. The colors represent synergy (green), trade-off (orange), and unclassified (apricot). Gray indicates statistically insignificant values with a $p > 0.05$, which were therefore excluded from the analysis. The proportion of synergies and trade-offs was the same (both 38%) within the water sector, whereas that of synergies (49–56%) was higher than that of trade-offs (43–44%) within the energy and food sectors (Figures 1, 3; Table 2). These interactions indicated that improving an indicator in each sector could improve the other indicator and vice versa. In general, as the water fee and usage increased, water stress could aggravate, consequently exhibiting a negative impact on the overall water security (Vaughray, 2011; Lankford et al., 2013). Thus, water usage (W6) and water fee (W12) were positively correlated with water stress (W4), whereas W4, W6, and W12 were negatively correlated with safe water (W1 and W2), water efficiency (W3), and water supply services (W13, W15, and W16). Moreover, W1-W2-W3 and W13-W15-W16 were positively correlated. Agricultural water consumption (W7) and water withdrawal (W14) showed synergies because

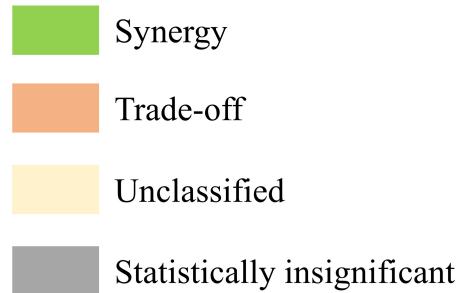


A Water

B Energy



C Food

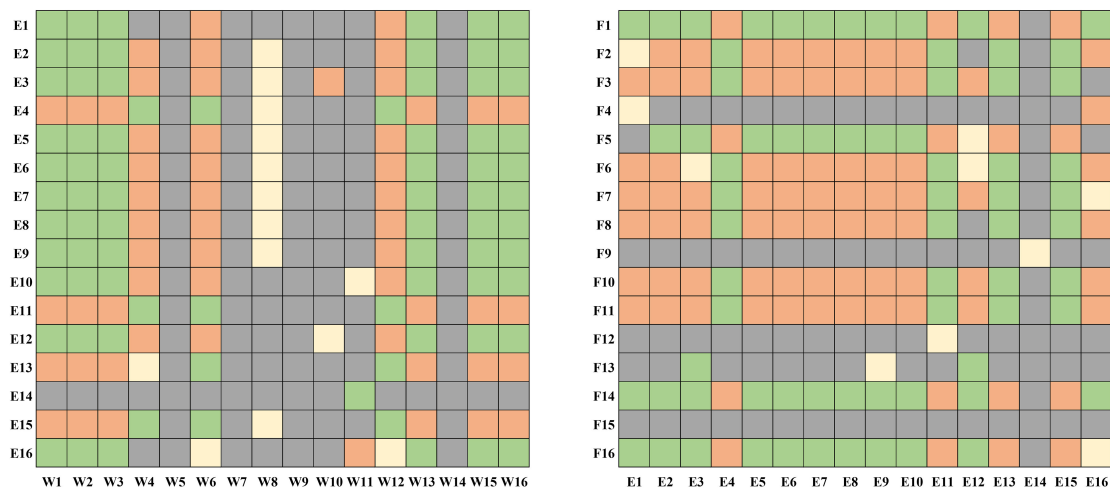


- W1 Safe drinking water
- W2 Safe sanitation water
- W3 Water use efficiency
- W4 Level of water stress
- W5 Lake and river area
- W6 Water usage per capita
- W7 Agricultural water consumption
- W8 Industrial water consumption
- W9 Municipal water consumption
- W10 Annual precipitation
- W11 Ground water for agriculture
- W12 Water supply service fee
- W13 Water supply service rate
- W14 Water withdrawals
- W15 Wastewater treatment
- W16 Sewerage supply rate

- E1 Access to clean fuels for cooking
- E2 Renewable energy consumption
- E3 Energy intensity
- E4 Emission from energy sector
- E5 Energy usage in agriculture
- E6 Electricity consumption per capita
- E7 Electricity generation by solar
- E8 Electricity generation by wind
- E9 Electricity generation by biofuels
- E10 Electricity generation by waste
- E11 Electricity generation by coal
- E12 Electricity generation by oil
- E13 Electricity generation by nature gas
- E14 Electricity generation by nuclear
- E15 Energy imports
- E16 Budget for low-carbon energy technologies

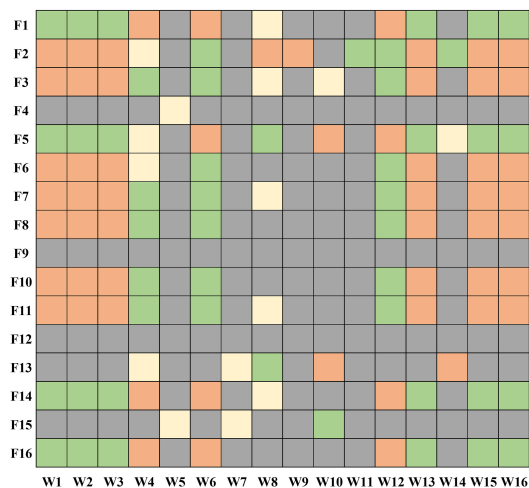
- F1 Stunring children
- F2 Overweight children
- F3 Value-added management of agriculture
- F4 Emission from agriculture sector
- F5 Food production index
- F6 Cereal production
- F7 Arable land
- F8 Cereal self-sufficiency rate
- F9 Fertilizer usage
- F10 Crops and livestock products import
- F11 Consumer food price index
- F12 Non-arable land
- F13 Agricultural productivity
- F14 Meat consumption
- F15 Food supply
- F16 Rail line density

FIGURE 1 Interactions within water, energy, and food (WEF) security indicators in South Korea: **(A)** Interactions within water security indicators, **(B)** interactions within energy security indicators, and **(C)** interactions within food security indicators.

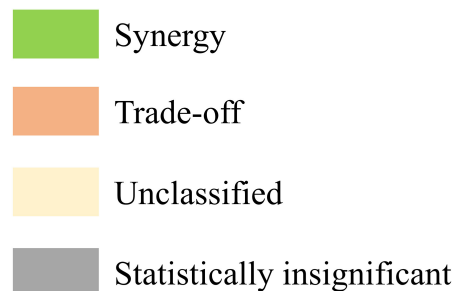


A Water-energy

B Energy-Food



C Water-food



- W1 Safe drinking water
- W2 Safe sanitation water
- W3 Water use efficiency
- W4 Level of water stress
- W5 Lake and river area
- W6 Water usage per capita
- W7 Agricultural water consumption
- W8 Industrial water consumption
- W9 Municipal water consumption
- W10 Annual precipitation
- W11 Ground water for agriculture
- W12 Water supply service fee
- W13 Water supply service rate
- W14 Water withdrawals
- W15 Wastewater treatment
- W16 Sewerage supply rate

- E1 Access to clean fuels for cooking
- E2 Renewable energy consumption
- E3 Energy intensity
- E4 Emission from energy sector
- E5 Energy usage in agriculture
- E6 Electricity consumption per capita
- E7 Electricity generation by solar
- E8 Electricity generation by wind
- E9 Electricity generation by biofuels
- E10 Electricity generation by waste
- E11 Electricity generation by coal
- E12 Electricity generation by oil
- E13 Electricity generation by nature gas
- E14 Electricity generation by nuclear
- E15 Energy imports
- E16 Budget for low-carbon energy technologies

- F1 Stunting children
- F2 Overweight children
- F3 Value-added management of agriculture
- F4 Emission from agriculture sector
- F5 Food production index
- F6 Cereal production
- F7 Arable land
- F8 Cereal self-sufficiency rate
- F9 Fertilizer usage
- F10 Crops and livestock products import
- F11 Consumer food price index
- F12 Non-arable land
- F13 Agricultural productivity
- F14 Meat consumption
- F15 Food supply
- F16 Rail line density

FIGURE 2 Interactions among water, energy, and food (WEF) security indicators in South Korea: **(A)** Interactions among water-energy security indicators, **(B)** interactions among energy-food security indicators, and **(C)** interactions among water-food security indicators.

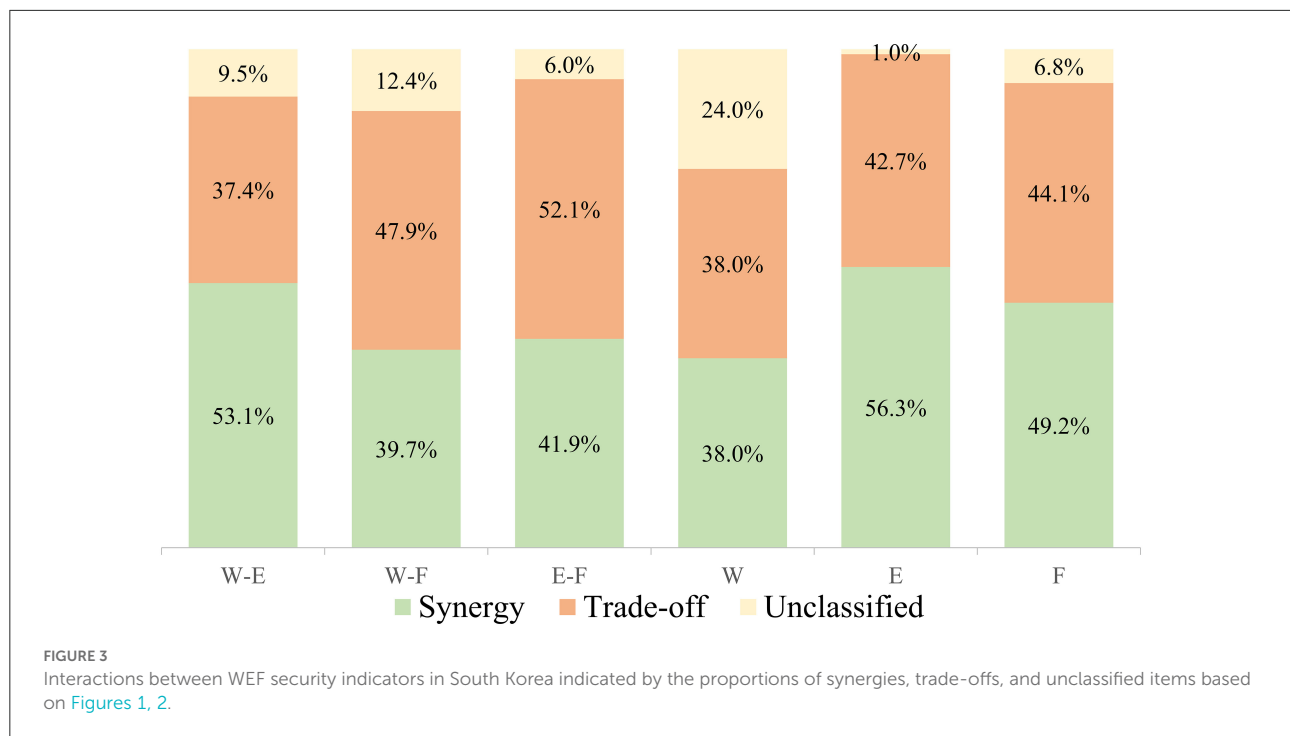


TABLE 2 Number of WEF interactions in Figure 1.

		Synergies	Trade-offs	Unclassified	Total interactions	Non-significant	Total
Within WEF security	Water	19	19	12	50	70	120
	Energy	58	44	1	103	17	120
	Food	29	26	4	59	61	120
Among WEF security	Water-energy	78	55	14	147	109	256
	Water-food	48	58	15	121	135	256
	Energy-Food	70	87	10	167	89	256
Total		302	289	56	647	481	1,128

South Korea uses ~60% of its water resources annually for agriculture (World Bank, 2021).

In the power generation field, renewable energies are environmentally friendly because fuel consumption and carbon emissions are significantly lower than those for non-renewable energies. Therefore, renewable energy indicators (solar: E7, wind: E8, biofuel: E9, and waste: E10) were negatively correlated with the carbon emissions in the energy field (E4), and non-renewable energy indicators (coal: E11 and nature gas: E13) were positively correlated with E4. Furthermore, because renewable energies have lower energy efficiency than non-renewable energies, E7, E8, E9, and E10 were positively correlated with energy intensity (E3), whereas an opposite trend was observed for E11 and E13. Contrastingly, oil-based electricity generation (E12) showed opposite correlations with E3 and E4, unlike other non-renewable energy indicators. This was probably because the operation of oil-fired plants has steadily

decreased since 1995, presently accounting for approximately only 1% of the total energy mix (International Energy Agency, 2021). Energy imports (E15) were negatively correlated with the budgets for low-carbon energy technologies (E16). These interactions were similar to those observed in previous studies, which reported that renewable energies could enhance energy security (Valentine, 2011; Hinrichs-Rahlwes, 2013; Gökgöz and Güvercin, 2018).

Furthermore, a well-developed food supply chain can reduce food prices (Bunte, 2006; Armendariz et al., 2015). Hence, the increase in rail line density (F16) and the consumer food price index (F11) were negatively correlated. Additionally, a negative correlation was observed between arable land (F7) and value-added management of agriculture (F3) and between F7 and F3 and the proportion of starving children (F1). Arable land and the value-added management of agriculture in South Korea are continuously decreasing (UN, 2021; World Bank, 2021); thus,

improving these problems could solve the hunger problem. As a decrease in domestic food production can be replaced by the corresponding food imports (Sandström et al., 2018), the food production index (F5) and the imports of crop and livestock products (F10) were negatively correlated. Moreover, F10 and F11 were positively correlated, highlighting the dependence on imports for food.

Interactions among WEF security indicators

This study captured interactions in which synergies (40–53%) and trade-offs (37–52%) showed similar proportions among the WEF sectors and discovered possibilities for improving WEF security (Figures 2, 3; Table 2). Many water indicators in the water and energy fields (safe: W1 and W2, efficiency: W3, and supply service: W13, W15, and W16) showed positive correlations with renewable energy-related indicators (E2: renewable consumption, solar: E7, wind: E8, biofuel: E9, and waste: E10) and negative correlations with non-renewable energy-related indicators (coal: E11 and natural gas: E13). Furthermore, indicators related to the water stress level (W4) and water usage per capita (W6) showed negative correlations with renewable energy-related indicators (E7, E8, E9, and E10), possibly because renewable energy consumes much less water than non-renewable energy (Larsen and Drews, 2019), which uses more water for cooling (Macknick et al., 2012). The water industry is highly energy-intensive because of its strong dependency on energy (Kenway et al., 2011; Plappally and Lienhard, 2012). Thus, the water supply service indicators (W13, W15, and W16) and emissions from the energy sector (E4) were negatively correlated.

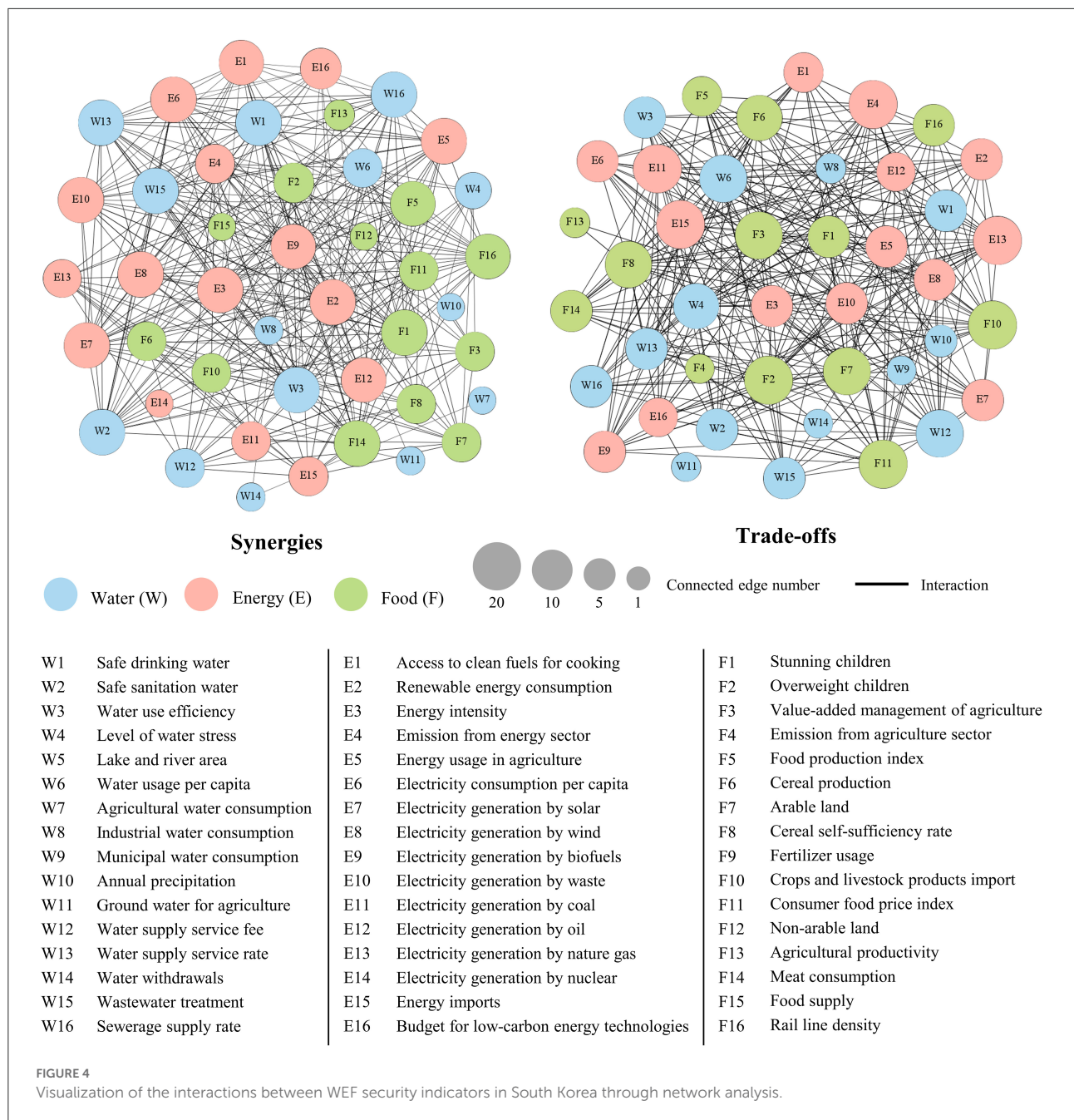
Regarding water and food fields, as arable land (F7) and cereal self-sufficiency rate (F8) increased, W4 and W6 increased because agriculture is water-intensive and sensitive to water stress (FAO, 2017). For similar reasons, W4 and the consumer food price index (F11) were positively correlated. Moreover, annual precipitation (W10) and food supply (F15) were positively correlated because the volume of available water for food production depends on precipitation (Achite et al., 2017). The water supply service fee (W12) was positively correlated with crop and livestock product imports (F10) because as water prices increase, domestic food prices increase, making people more dependent on cheaper imported foods (Johansson, 2000). In the livestock industry, meat has a high water footprint, which includes the amount of water consumed to obtain products, including feed (Hoekstra and Chapagain, 2011). According to Mekonnen and Hoekstra (2012), for crops, the water footprint for 1 kg of potato, beans, and rice is 900, 1,800, and 4,300 L, respectively, whereas for meat, it is 15,500, 4,800, and 3,900 L for 1 kg of beef, pork, and

chicken, respectively. Therefore, when W4 increased, meat consumption (F14) decreased, showing a negative correlation. Further, the indicators related to water supply services (W13, W15, and W16) showed positive correlations with the food production index (F5), indicating that food production becomes more efficient when the water supply system is well-developed (Bhagwat, 2019).

Regarding energy and food fields, the indicators related to agricultural productivity and availability (value-added management of agriculture: F3, cereal production: F6, and cereal self-sufficiency rate: F8) showed negative correlations with renewable energy indicators (E2, E7, E8, E9, and E10) and positive correlations with non-renewable energy indicators (E11 and E13). This is because the levelized cost of electricity from renewable energies in South Korea is higher than that from non-renewable energies (Hong et al., 2019). However, renewable energies are expected to achieve grid parity owing to improvements in efficiency and technology development (Breyer and Gerlach, 2013; International Renewable Energy Agency, 2021), but such correlations could be reversed in the near future. The food industry is an energy intensive industry that consumes ~30% of the total global energy (FAO, 2017). Accordingly, F3, F6, and F8 showed synergies with energy imports (E15), whereas crop and livestock product imports (F10) were negatively correlated with energy consumption in agriculture (E5). Fluctuations in the oil price significantly affect food prices (Esmaili and Shokoohi, 2011) because food production depends heavily on non-renewable energy resources (Pelletier et al., 2011). Therefore, diversifying energy consumption in the food sector to renewable energy could stabilize food prices (Taghizadeh-Hesary et al., 2019).

Networks of interactions

Figure 4 shows the interaction networks within and among the WEF sectors in South Korea. The diagram on the left shows synergy interactions, whereas the diagram on the right shows trade-off interactions. Furthermore, each node indicates one of the 48 WEF indicators, and edges represent interactions between two indicators on the basis of Figures 1, 2. The higher the number of connected edges, the larger the node. Interactions are expressed in each network by distinguishing between synergies and trade-offs. The indicators of the energy field had the highest influence across all synergy and trade-off networks. Nonetheless, the water and food fields also contributed largely to the networks. The number of edges between the nodes (interactions) ranged from 1 to 21 per indicator. Furthermore, among the top 10 indicators that had the largest number of connected edges, the energy field had the largest influence (Table 3). Table 3 shows the most influential indicators with 20 or more connected edges, implying that these indicators further influenced 20 or more other indicators.



Among the energy-related indicators in the synergy networks, the indicators related to renewable energies (E2, E7, E8, and E10) were the most influential, indicating that increasing the proportion of renewable energies can improve the WEF security (Wicaksono and Kang, 2019; Putra et al., 2020) and positively influence the other 20 indicators. Energy intensity (E3) and energy consumption in agriculture (E5) also showed similar effects. This is because higher energy intensity corresponds to lower water consumption during

energy generation, and less food resources; moreover, the proportion of renewable energies for power consumption in South Korea is steadily increasing (International Energy Agency, 2021). Since food and energy industries are water intensive (FAO, 2017; Bhagwat, 2019), the indicators related to water infrastructure, safe water (W1 and W2), water efficiency (W3), and water supply services (W13, W15, and W16) in the water field had the largest impact. Water infrastructure refers to water-related facilities, such as dams, reservoirs, water supply

TABLE 3 Top 10 indicators with nodes having 20 or more edges in Figure 4.

Interaction	Sector	Node (number of edges)
Synergy	Water	W1 (20), W2 (20), W3 (20), W13 (20), W15 (20), W16 (20)
	Energy	E2 (20), E3 (20), E5 (20), E6 (20), E7 (20), E8 (20), E10 (20)
	Food	F1 (20), F14 (20)
Trade-off	Water	W6 (20), W12 (20)
	Energy	E4 (21), E11 (21), E13 (21), E15 (21)
	Food	F2 (21), F10 (21), F11 (21), F3 (20), F7 (20)

systems, and sewage facilities, including the above-mentioned water-related indicators (Monsma et al., 2009). The current water infrastructure in South Korea is severely deteriorating (Kang, 2019). Thus, it needs major improvements to ensure the sustainability of these indicators. Since meat production has a high water footprint (Hoekstra and Chapagain, 2011), meat consumption (F14) showed many interactions with other indicators. Observations of the food consumption patterns of South Korea indicated that meat consumption has been increasing, whereas cereal consumption has been decreasing since 1980 (Korea Rural Economic Institute, 2019b), suggesting that switching to a cereal-based diet can promote water, energy, and food security.

The energy-related indicators showed contrasting patterns in the trade-off and synergy networks. The indicators related to non-renewable energies (electricity generation by coal and natural gas: E11 and E13, emission from energy sector: E4, and energy imports: E15) had the highest influence in the energy field. The emissions from the energy industry of South Korea are extremely high because the industry largely depends on thermal power for energy and on imports of non-renewable energy sources (International Energy Agency, 2021; Ministry of Environment of South Korea, 2021). Moreover, the thermal power industry is water intensive and can sometimes disrupt the water supply to surrounding villages during a drought (Zhang et al., 2017). Because water is an important resource for food and energy industries, water usage per capita (W6) and the water supply service fee (W12) could compromise WEF security. Interestingly, interactions with precipitation (W10), which is closely related to water availability, were few, implying that even if sufficient water is available, the impacts of W6 and W12 on water security are low if water infrastructure management and use are inefficient. Arable land (F7) and the value-added management of agriculture (F3) had the most negative impact on WEF security because the food industry is directly and indirectly associated with water and energy sectors (Daher and Mohtar, 2015; Vandone et al., 2018). Similarly, the nodes, namely, crop and livestock product imports (F10) and consumer

food price index (F11), which are F3 elements, had the largest impact in the trade-off network (Lu and Dudensing, 2015).

Discussion

The current research presents two main findings. First, the interactions of indicators associated with WEF security were quantified, thereby realizing the first objective of the study. The results confirm that WEF sectors, which are inter-linked, interact with each other. Among all interactions, the proportion of synergies and trade-offs was higher, while the proportion of unclassified correlations was lower than those observed in previous studies in South Asian (Putra et al., 2020) and Central Asian (Hao et al., 2022) countries. These findings suggest that the WEF sectors in South Korea are complexly interconnected and that WEF security can be improved through the nexus approach (Organization for Economic Cooperation and Development, 2018). Using the approach outlined here, the author could discuss different ways of maximizing synergies while minimizing trade-offs, which is especially important in countries with WEF insecurity.

Second, the most influential indicators and policy priorities for an effective resource management in the WEF security nexus were analyzed, thus achieving the second and third research objectives. The corresponding results can help identify resource management policies that should be prioritized to ensure efficient WEF security (Flammini et al., 2014; Mahlknecht et al., 2020). For example, renewable energy-related and non-renewable energy-related indicators showed mostly positive and negative influences on WEF security, respectively, in the energy sector. If the proportion of renewable energies is increased in the energy mix, WEF security could be improved by maximizing synergies and minimizing trade-offs (Wicaksono and Kang, 2019; Putra et al., 2020). In the water sector, improving the water infrastructure and efficiency was the most effective strategy. Currently, the water infrastructure in South Korea is deteriorating rapidly, and thus, investments and repairs to maintain WEF security are necessary (Kang, 2019). Simultaneously, controlling water consumption and prices, which negatively influence WEF security, is important. In the food sector, the value-added management of agriculture was the most important. Notably, meat consumption had the most positive influence on WEF security. South Korea relies heavily on imports for meat products, with the import trend increasing overtime (Korea Rural Economic Institute, 2019a). The meat industry is both water and energy intensive (Mekonnen and Hoekstra, 2012), and thus, importing meat products would reduce the consumption of energy and water resources, which is why meat industry was the most influential indicator.

Overall, this analysis indicates that efforts in one area alone cannot improve WEF security as a whole. For example, even if the proportion of renewable energy and food production

increases rapidly if the water supply is impaired, WEF security will deteriorate in general. WEF security could be ensured effectively when improving indicators in each field that have the highest influence on other fields.

However, a limitation of this study was that the selected indicators only covered a part of resource security. Owing to the nature of the applied method, which requires pairs of sorted data, the availability of data largely affected the selection of indicators. It is expected that more interactions could be analyzed in the future if more indicators related to WEF security are considered. Moreover, because linear relationships were applied to compare the pairs of data points, the relationships among the three resources (WEF) could not be considered concurrently, but individual relationships between two resources were analyzed by pairing them thrice (W-E, W-F, and E-F). The effects of the three resources could be examined simultaneously if a simulation model, which can simultaneously explore linear and non-linear relationships, is utilized. The implications of this study provide substantial reference to conduct such future studies. Furthermore, for its active utilization, the nexus system should be combined with decision-making fields such that policies can respond to the future demands of WEF resources. This can be achieved by applying various WEF food resource scenarios.

Conclusions

In this study, a systematic framework was proposed to determine the interactions between WEF security in South Korea using two quantitative approaches, namely, Spearman's rank correlation and network analysis to better understand WEF security on a national scale. The results indicated that WEF sectors are closely interconnected, and thus, WEF security could be ensured if synergies are maximized and trade-offs are minimized regarding the interactions in WEF security. Furthermore, the interaction between energy or energy-related sectors was found to be the highest, indicating that managing energy security is the most effective area to improve WEF security. Specifically, reducing the proportion of non-renewable energies and increasing the proportion of renewable energies could contribute significantly to WEF security, followed by the water infrastructure and value-added management of agriculture. An integrated approach *via* the WEF security nexus will provide a basis for sustainable resource management, and mutual feedback will enable a more efficient use of each resource. In addition, a sustainable and effective resource management could be achieved through policies prioritized for the most interactive indicators.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/[Supplementary material](#).

Author contributions

This research was developed and completed by DA. All methodologies, analyses, and writing were conducted by DA.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/frwa.2022.943053/full#supplementary-material>

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