Evaluating The Adoption of Industry 4.0, Sustainability, and Circular Economy Drivers to Achieve Sustainable Development Goals-Oriented Agri-Food Supply Chains

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Abstract

The consideration of Industry 4.0, sustainability, and Circular Economy (I4.0-S-CE) drivers plays a pivotal role in the development of agri-food supply chains (AFSCs) that aim to achieve sustainable development goals (SDGs). Establishing SDGs-oriented AFSCs is critical for meeting the agricultural needs of developing countries, prioritizing agricultural SDGs, and developing effective agricultural policies. However, this requires integrating I4.0-S-CE into AFSCs. This study is the first to propose this integration to create SDGs-oriented AFSCs, aiming to identify key I4.0-S-CE drivers and rank agricultural SDGs in developing countries. A literature review and expert opinions were utilized to identify the three main drivers and eighteen sub-drivers to achieve this goal. Then, the importance level of each driver was determined using the Fuzzy Best Worst Method (FBWM), and the agricultural SDGs were ranked based on their Fuzzy Weighted Aggregated Sum Product Assessment (FWASPAS) scores. The validity of the findings was assessed through comparison with other decision-making techniques and one-at-a-time sensitivity analysis. This study demonstrates how the integration of I4.0-S-CE drivers contributes to the achievement of the SDGs-oriented AFSCs. Moreover, this study offers valuable guidance to practitioners regarding the prioritization of agricultural SDGs and identifying drivers to support the development of SDGs-oriented AFSCs in developing countries.

Keywords: Agri-food supply chain, circular economy, sustainability, SDGs, FBWM, FWASPAS

Introduction

Environmental and social challenges caused by climate change, global warming, urbanization, industrialization, and population growth seriously threaten to achieve the Sustainable Development Goals (SDGs) (Lahane & Kant, 2022). Several sustainability practices and concepts have been developed to achieve the SDGs, such as Industry 4.0 technologies (I4.0), sustainability, and circularity. I4.0 entails leveraging information, communication, and intelligence technologies to achieve circular solutions (Bai et al., 2020). The adoption of I4.0, such as big data, blockchain, the Internet of Things (IoT), artificial intelligence (AI), and machine learning (ML) (Sutar et al., 2024; Sharma et al., 2024), enables the establishment of circular agri-food supply chains (AFSCs), enhancing traceability and transparency while reducing food loss and waste (Joshi et al., 2024; Kayikci et al., 2022a). Therefore, I4.0 is a new foundation for circularity in agricultural processes and contributes to achieving the SDGs (Annosi et al., 2020; Bai et al., 2020). This demonstrates the need to integrate I4.0 with sustainability and circularity issues to achieve the SDGs.

The United Nations (UN) introduced 17 SDGs to achieve a more sustainable and circular future. Incorporating sustainability and circular economy (CE) principles into the SDGs helps to improve economic growth, environmental protection, and social well-being (UN, 2015; Belaud et al., 2019). Organizations focused on achieving the SDGs in their AFSCs must consider the relationships between

I4.0, sustainability, CE, and the SDGs. However, the integration of I4.0 with sustainability and CE (I4.0-S-CE) and the study of their impact on SDGs-oriented AFSCs are still in their early stages. Therefore, more research is needed focusing on the impacts of the integrated I4.0-S-CE approach on the achievement of SDGs-oriented AFSCs.

SDGs-oriented AFSCs describe agricultural supply chains in which the production, processing, packaging, distribution, consumption, and disposal stages of agri-food products are managed following the principles of sustainability, CE, and the SDGs (FAO, 2021). CE drives sustainability and the SDGs, while I4.0 strengthens this link through its complementary alignment with CE (Dantas et al., 2021; Schroeder et al., 2019). Thus, CE is closely linked to the economic, environmental, and social pillars of sustainability, driven by the objectives outlined in the UN's 2030 Agenda for SDGs (Corona et al., 2019; Geissdoerfer et al., 2017; Kirchherr et al., 2016). As a driving force behind the SDGs (Geissdoerfer et al., 2017), CE aims to reduce waste and increase recycling and recovery from waste (Mishra et al., 2022; Kirchherr et al. 2016) for circular agricultural production. Therefore, AFSCs based on the reduction, reuse, recycling, and recovery practices of CE (Bocken et al., 2018; Bag et al., 2021a; Zhu et al., 2019; Ahmed et al., 2024) can contribute to the achievement of SDGs-oriented AFSCs.

SDGs-oriented AFSCs are essential for addressing the increasing food demand resulting from economic, environmental, and social challenges. These systems aim to eradicate poverty and hunger while improving food security by optimizing resource use, minimizing waste, and reducing emissions in supply chains. However, practitioners need to understand how to start and what factors to consider in this process. The primary motivation for this study is to explore the key drivers of I4.0-S-CE that support the development of SDGs-oriented AFSCs, particularly in developing countries. Identifying the key drivers of these AFSCs is essential for achieving the SDGs, preventing food loss and waste (Esposito et al., 2020), biodiversity conservation, and greenhouse gas emissions reduction (Zhang et al., 2022; Negra et al., 2020).

While I4.0-S-CE nexus is a relatively new concept for developing countries like Turkey, its significance for emerging SDGs-oriented AFSCs has received limited attention in the existing literature. Recent studies (Kumar et al., 2024; Dwivedi et al., 2022; Kayikci et al., 2022b; Bag et al., 2021b; Fatimah et al., 2020) have investigated I4.0-S-CE nexus in the context of other industries in developing countries. While aspects of I4.0 and agricultural circularity have been explored in developing countries (Perçin, 2022; Dwivedi et al., 2022; S. Kumar et al., 2021), the full integration and potential of these concepts in sustainable AFSCs is still in the relatively early stages of adoption. Therefore, AFSCs in developing countries such as Turkey strive to achieve specifically SDGs-oriented AFSCs by embracing I4.0-S-CE. Adopting and integrating I4.0-S-CE is urgently needed to advance these efforts. Thus, the synergy within the I4.0-S-CE nexus is crucial for addressing hunger, meeting nutritional needs, ensuring food security, and reducing food loss and waste (Kumar et al., 2022). Moreover, AFSCs in Turkey have a direct impact on agricultural SDGs. Agricultural SDGs aim to tackle climate change (SDG13) and global warming while also promoting access to land (SDG 15), water (SDG 6), and clean energy

(SDG7). By efficiently utilizing resources through integrated I4.0-S-CE, poverty (SDG1), hunger (SDG2), as well as healthy lives (SDG3) and sustainable consumption and production (SDG12) can be improved, ultimately contributing to the achievement of the SDGs (Schroeder et al., 2019).

Although numerous studies (Pandya et al., 2023; Akbari & Hopkins, 2022; Reis et al., 2021; Nara et al., 2021; Ejsmont et al., 2020; Ahmed et al., 2024) have been published in recent years examining the relationships between I4.0 and sustainability issues, no specific study currently focuses on the I4.0-S-CE nexus and its implications for SDGs-oriented AFSCs. This research gap highlights the need for a framework that identifies the drivers of the I4.0-S-CE nexus in achieving SDGs-oriented AFSCs. Understanding these drivers is crucial for practitioners and policymakers to develop AFSCs that align with the agricultural SDGs. Therefore, this study addresses the following research questions (RQs):

RQ1. *What are the key drivers of the I4.0-S-CE nexus necessary for SDGs-oriented AFSCs?*

RQ2. *What is the prioritized order of importance of agricultural SDGs in a developing country?*

I4.0-S-CE practices are essential for achieving sustainability, promoting CE and resilience (Sutar et al., 2024; Ramos et al., 2024), and facilitating the achievement of SDGs in agricultural systems. To the authors' knowledge, no study has investigated the development of SDGs-oriented AFSCs through the lens of integrated I4.0-S-CE applications. Therefore, the study's main contribution is identifying key I4.0-S-CE drivers that enable SDGs-oriented AFSCs in developing countries and highlighting their role in achieving agricultural SDGs. Furthermore, it will assist policymakers in creating strategies and policies to support agricultural SDGs and promote the transition to SDGs-oriented AFSCs.

The remainder of the paper is structured as follows. Section 2 provides a detailed literature review, Section 3 explains the research methodology, and Section 4 presents the case study. Section 5 presents the validation of the results, while sections 6 and 7 deal with the discussion and conclusions, respectively.

Literature Review

The literature review is focused on I4.0, sustainability, and CE and their impacts on agricultural SDGs in transition to SDGs-oriented AFSCs. For this purpose, the Scopus database was searched using various keyword combinations such as "I4.0+CE", "I4.0+sustainability/SDGs", "CE+ sustainability/SDGs" and "AFSC+SDGs". The search was narrowed down to journal articles published in English between 2017 and June 2023. A total of 98 articles were found, 65 of which were used in the relevant parts of the study. Table 1 shows some relevant studies that can provide a general assessment of the review process.

[INSERT TABLE 1 HERE]

Linking AFSCs and the SDGs

Many of the challenges highlighted in the SDGs, such as food security and quality, food loss and waste, hunger and poverty, require the redesign of AFSCs to make them sustainable and circular. Circular AFSCs can only be achieved by integrating the principles of sustainability and CE (Geissdoerfer et al., 2017) into the design process of agri-food systems. These principles help AFSCs achieve SDG1, SDG2, SDG12, and SDG13 (Zisopoulos et al., 2017). Nhemachena et al. (2018) considered the targets of SDG1, SDG2, SDG6, SDG7, and SDG15 to develop an agricultural SDG index, while Whitcraft et al. (2019) highlighted the importance of SDGs related to agriculture such as SDG1, SDG2, SDG6, SDG12, SDG13, and SDG15. Furthermore, FAO (2015) and Negra et al. (2020) emphasized that AFSCs directly benefit from SDGs related to agriculture such as ending poverty (SDG1) and hunger (SDG2), ensuring good health (SDG3), conserving water (SDG6), energy (SDG7), and life on land (SDG15), achieving sustainable consumption and production (SDG12), and combating climate change and its impacts (SDG13).

The relevance of I4.0 to SDGs-oriented AFSCs

The key to building SDGs-oriented AFSCs requires the identification of the linkages between I4.0-S-CE and SDGs. I4.0 supports SDGs-oriented AFSCs by providing traceability, transparency, and sustainability of products from farm to fork. In this process, cloud computing, the Internet of Things (IoT), Big Data, Blockchain, sensors and robotics, AI and ML provide smart, connected, agile, and autonomous systems for managing agricultural data (Lezoche et al., 2020; Sutar et al., 2024; Sharma et al., 2024). Smartphones, computers, remote sensing tools, maps, software, and databases are also used to collect, store, transmit, and analyse data (Wolfert et al., 2017). Moreover, drone-based imagery AI applications are used for pest-disease detection and management, while IoT, agricultural aerial vehicles, satellites, and smart sensors provide real-time data for managing operations such as irrigation, fertilization, soil conservation, nutrient quality, plant growth, climatic conditions, and crop yield (Wolfert et al., 2017; Whitcraft et al., 2019). In addition, blockchain, IoT, and Big Data enable product identification, tracking, and tracing throughout the AFSCs (Akyazi et al., 2020). These technologies help increase productivity, reduce food loss and waste, limit carbon emissions, and improve food quality and safety (Kayikci et al., 2020). Thus, I4.0 is an important building block that improves economic returns, social fairness, and environmental sustainability (Belaud et al., 2019) by facilitating the transition to SDGs-oriented AFSCs.

Sustainability and CE perspectives and their relationship with SDGs-oriented AFSCs

More than 0.8 billion people face hunger and malnutrition today, and one-third of the food produced is wasted. Furthermore, the agri-food sector generates over 3.3 million tonnes of emissions and causes environmental impacts, including waste, overproduction, fertiliser use, water scarcity, and soil pollution (FAO, 2020). AFSCs need to be managed according to sustainability, CE, and resilience perspectives to address these issues.

The SDGs related to CE support the promotion of more sustainable and circular agriculture. For example, SDG12 aims to prevent food loss and waste by ensuring resource efficiency. It also aims to improve food resource utilisation, reduce waste, increase productivity, and support equitable access to nutritious food (Islam & Zheng, 2024). SDG1 and SDG2 contribute to eradicating poverty and hunger by achieving circular agri-food systems. SDG7 aims to use renewable energy, while SDG13 supports the fight against climate change. Other SDGs are directly or indirectly related to CE, such as SDG3 on good health, SDG6 on water conservation, and SDG15 on soil quality (Barros et al., 2020; Zhang et al., 2022). Therefore, adopting CE principles in AFSCs reduces food loss and waste, provides greater economic and environmental returns, and improves social well-being (Kusumowardani et al., 2022). Furthermore, CE plays a crucial role in enabling sustainable development (Zhu et al., 2019; Mishra et al., 2022). The 4Rs of CE, namely reduce, reuse, recycle, and recover, contribute to the achievement of SDGs-oriented AFSCs by increasing food security and safety, preserving natural resources, and reducing greenhouse gases (Kumar et al., 2022; Kusumowardani et al., 2022; Zhang et al., 2022).

Methodology

Currently, a gap exists in the literature concerning the identification of drivers for I4.0-S-CE in transitioning to SDGs-oriented AFSCs. Additionally, no studies have examined how these drivers affect the ranking of agricultural SDGs. FBWM provides a significant advantage over other weighting techniques. It determines the weights of drivers by comparing them to the fuzzy best and worst reference points for different decision-makers. Since human judgments involve uncertainty, FBWM reduces the number of comparisons and uses linguistic terms instead of crisp values. This shows that FBWM produces more accurate results, saves time, and simplifies calculations than other methods (Ecer & Pamucar, 2020). Furthermore, using the weights derived from the FBWM, FWASPAS ranks agricultural SDGs according to their significance.

This study integrates expert linguistic judgments to address the inherent uncertainties of the problem. In the first phase, the drivers/criteria and sub-drivers/sub-criteria were identified through a literature review and expert opinions then weighted using the FBWM. In the second phase, the FWASPAS was employed to rank the SDGs of the AFSCs. The third phase involved a validation analysis, which included comparing the results with FTOPSIS (Fuzzy Technique for Order of Preference by Similarity to Ideal Solution), FARAS (Fuzzy Additive Ratio Assessment) and FSAW (Fuzzy Simple Additive Weighting) methods, as well as conducting a one-at-a-time sensitivity analysis. Figure 1 shows the framework of the proposed model.

[INSERT FIGURE 1 HERE]

The basic definitions of fuzzy sets

In this section, the basic definitions of fuzzy sets are explained as follows (Guo & Zhao, 2017; Ecer & Pamucar, 2020):

Definition 1. A fuzzy number is a special fuzzy set $\tilde{A} = \{(x, \mu_{\tilde{A}}(x)),\ x \in R\}$, where x takes values on the real line $R: -\infty \leq x \leq \infty$, and $\mu_{\tilde{A}}(x)$ is a membership function in the closed interval $[0,1]$.

Definition 2. A Triangular Fuzzy Number (TFN) $\tilde{A}$ is defined as $\tilde{A} = (l, m, u)$, where $l \leq m \leq u$. The parameters l, m, u represent the lower bound value, the center, and the upper bound value of $\tilde{A}$, respectively. The membership function of $\tilde{A}$ can be expressed by Eq (1).

$$\mu_{\tilde{A}}(x) = \begin{cases} 0, & x < l \\ \dfrac{x-l}{m-l}, & l \leq x \leq m \\ \dfrac{u-x}{u-m}, & m \leq x \leq u \\ 0, & x > u \end{cases} \tag{1}$$

Definition 3. Let $\tilde{A} = (l_1, m_1, u_1)$ and $\tilde{B} = (l_2, m_2, u_2)$ be two TFNs and $\lambda > 0$. In this case, the following operational laws for two TFNs can be determined according to Eqs (2) to (6).

$$\tilde{A} \oplus \tilde{B} = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \tag{2}$$

$$\tilde{A} \otimes \tilde{B} = (l_1 l_2, m_1 m_2, u_1 u_2) \tag{3}$$

$$\tilde{A} \ominus \tilde{B} = (l_1 - u_2, m_1 - m_2, u_1 - l_2) \tag{4}$$

$$\frac{\tilde{A}}{\tilde{B}} = \left(\frac{l_1}{u_2}, \frac{m_1}{m_2}, \frac{u_1}{l_2}\right) \tag{5}$$

$$\lambda\tilde{A} = \lambda(l_1, m_1, u_1) = \lambda l_1, \lambda m_1, \lambda u_1 \tag{6}$$

Definition 4. Let $\tilde{A} = (l_1, m_1, u_1)$ and $\tilde{B} = (l_2, m_2, u_2)$ be two TFNs. Then, the distance between $\tilde{A}$ and $\tilde{B}$ can be obtained by Eq (7).

$$d(\tilde{A}, \tilde{B}) = \sqrt{(1/3)((l_1 - l_2)^2 + (m_1 - m_2)^2 + (u_1 - u_2)^2)} \tag{7}$$

Definition 5. Let $\tilde{A}_j = (l_j, m_j, u_j)$ be a TFN. Ranking of the TFN $\left(R(\tilde{A}_j)\right)$ is obtained by Eq (8).

$$R(\tilde{A}_j) = (l_j + 4\, m_j + u_j)/6 \tag{8}$$

FBWM

The traditional methods, AHP and ANP, require many pairwise comparisons to determine criterion weights. Furthermore, if the comparison matrices contain inconsistencies, the evaluation must be revised. BWM, developed by Rezaei (2015), addresses concerns about consistency by requiring fewer pairwise comparisons. Another advantage is its utilization of a non-linear model that incorporates reference comparisons to determine criterion weights (Ecer & Pamucar, 2020). FBWM, introduced by Guo & Zhao (2017), facilitates the application of BWM methods in uncertain environments for solving real-world decision problems. FBWM uses linguistic variables to compare the criteria with the best and worst fuzzy reference points, resulting in fewer pairwise comparisons to determine the criteria weights. This section presents the steps of FBWM as follows (Ghoushchi et al., 2019; Ecer & Pamucar, 2020):

Step 1. Identify the best (C_B) and worst (C_W) drivers. The expert team determines and evaluates a set of drivers. Then, the best criterion (C_B) and the worst criterion (C_W) are identified by evaluating the set of drivers and considering the experts' opinions.

Step 2. Use a linguistic scale for pairwise comparisons of the drivers. The experts' preferences regarding the drivers are obtained using the linguistic terms given in Table 2 and transformed into corresponding TFNs.

Step 3. Obtain the pairwise comparisons of C_B and C_W with other drivers. The expert team determines the degree of importance of C_B over all the other criteria and the degree of importance of all the criteria over C_W, using the linguistic scale shown in Table 2.

[INSERT TABLE 2 HERE]

$\tilde{A}_B = (\tilde{a}_{B1}, \tilde{a}_{B2}, \dots, \tilde{a}_{Bn})$ is defined fuzzy Best-to-Others (BO) vector, where $\tilde{A}_B$ identifies the BO vector. Also $\tilde{a}_{Bj}$ represents the fuzzy preference of C_B over the criterion j $(j = 1,2 \dots, n)$, thus it can be argued that $\tilde{a}_{BB} = (1,1,1)$. On the other hand, $\tilde{A}_W = (\tilde{a}_{1W}, \tilde{a}_{2W}, \dots, \tilde{a}_{nW})$ is defined fuzzy Others-to-Worst (OW) vector, where $\tilde{A}_W$ identifies the OW vector. Also, $\tilde{a}_{jW}$ represents the fuzzy preference of the criterion j over C_W $(j = 1,2 \dots, n)$, thus it can be argued that $\tilde{a}_{WW} = (1,1,1)$.

Step 4. Calculate the normalized weights of drivers. Model (9) presents a non-linear programming formulation based on the components derived from the BO and OW vectors. In this model, $\widetilde{w}_j = \left(l_j^w, m_j^w, u_j^w\right)$, $\widetilde{w}_B = (l_B^w, m_B^w, u_B^w)$, $\widetilde{w}_W = (l_W^w, m_W^w, u_W^w)$ respectively represent the fuzzy weight of criterion j, best criterion C_B, and worst criterion C_W, where l, m, and u respectively represent the lower, medium, and upper values.

$$min\xi^*$$

$$s.t.\begin{cases} \left|\dfrac{l_B^w, m_B^w, u_B^w}{l_j^w, m_j^w, u_j^w} - l_{BJ}, m_{BJ}, u_{BJ}\right| \le (k^*, k^*, k^*) \\ \left|\dfrac{l_j^w, m_j^w, u_j^w}{l_W^w, m_W^w, u_W^w} - l_{jW}, m_{jW}, u_{jW}\right| \le (k^*, k^*, k^*) \\ \sum_j R\,(\widetilde{w}_j) = 1 \\ l_j^w \le m_j^w \le u_j^w \\ l_j^w \ge 0 \\ j = 1,2, \dots n \end{cases} \tag{9}$$

where $\tilde{\xi} = \left(l^\xi, m^\xi, u^\xi\right)$; $l^\xi \le m^\xi \le u^\xi$ and $\tilde{\xi} = (k^*, k^*, k^*)$; $k^* \le l^\xi$. Then, optimal fuzzy weights $\widetilde{w}^* = (\widetilde{w}_1^*, \widetilde{w}_2^*, \dots, \widetilde{w}_n^*)$ and optimal ξ^*can be obtained by solving the Model (9). Then $R\left(\tilde{A}_j\right)$ given in Eq (8) is used to transform the fuzzy weight of criterion to crisp weight. The CI for different linguistic terms in FBWM is provided in Table 2. Finally, the consistency ratio (CR) can be calculated using the equation $CR = \frac{\xi^{k^*}}{CI}$ where $CR < 0.1$ is considered acceptable.

FWASPAS

In this section, the steps of FWASPAS are given as follows (Turskis et al., 2015):

Step 5. Calculate the weighted normalised fuzzy decision matrix. Let $\widetilde{A}_J = (l_1, m_1, u_1)$ and the optimal fuzzy weights $\widetilde{w}_J = (\widetilde{w}_1, \widetilde{w}_2, \ldots, \widetilde{w}_n)$.

The linear normalised $\widetilde{A}_J$ is given by Eq (10).

$$\widetilde{A}_J = \left(l_{ij}/u_j^+, m_{ij}/u_j^+, u_{ij}/u_j^+\right) \text{ and } u_j^+ = max_i u_{ij} \tag{10}$$

The weighted normalised fuzzy decision matrix for the weighted sum model (WSM) can be obtained by Eq (11).

$$\widetilde{\widetilde{A}}_J = \widetilde{A}_J * \widetilde{w}_j \qquad j = 1, 2 \ldots, n \tag{11}$$

The weighted normalised fuzzy decision matrix for the weighted product model (WPM) can be computed by Eq (12).

$$\overline{\overline{A}}_J = \tilde{A}_j^{\widetilde{w}_j} \qquad j = 1, 2 \ldots, n \tag{12}$$

Step 6. Calculate the optimality function values of alternatives.

Optimality function of the WSM for each alternative is obtained by Eq (13).

$$\widetilde{Q}_i = \sum_{j=1}^{n} \widetilde{\widetilde{A}}_J \qquad i = 1, 2 \ldots, m \tag{13}$$

Optimality function of the WPM for each alternative is computed by Eq (14).

$$\tilde{P}_i = \prod_{j=1}^{n} \overline{\overline{A}}_J \qquad i = 1, 2 \ldots, m \tag{14}$$

The centre of area method is applied for defuzzification of WSM and WPM based on Eqs (15) and (16).

$$\mathrm{Q_i} = \frac{1}{3}(\tilde{Q}_{l1} + \tilde{Q}_{m1} + \tilde{Q}_{u1}) \qquad i = 1, 2 \ldots, m \tag{15}$$

$$\mathrm{P_i} = \frac{1}{3}(\tilde{P}_{l1} + \tilde{P}_{m1} + \tilde{P}_{u1}) \qquad i = 1, 2 \ldots, m \tag{16}$$

Step 7. Determine the integrated utility function values of alternatives.

The integrated utility function values for each alternative are obtained by applying Eqs (17) and (18).

$$K_i = \lambda \sum_{j=1}^{m} Q_i + (1 - \lambda) \sum_{j=1}^{m} P_i \quad \lambda = 0, \ldots, 1, \quad 0 \le K_i \le 1 \tag{17}$$

$$\lambda = \frac{\sum_{i=1}^{m} P_i}{(\sum_{i=1}^{m} Q_i + \sum_{i=1}^{m} P_i)} \tag{18}$$

Step 8. Determine the ranking results of alternatives. The maximum value of K_i is chosen to rank the alternatives in descending order.

Case Study

This section describes the case study adopted for the proposed model. The proposed model is divided into three sub-sections: the data collection process, FBWM, and FWASPAS methods.

Data collection

SDGs-oriented AFSCs are essential tools that should be implemented in developing countries due to their ability to ensure food security and quality and eliminate food losses and waste. Therefore, the drivers of I4.0-S-CE that enable the development of SDGs-oriented AFSCs were first identified. Then the agricultural SDGs that play a key role in emerging SDGs-oriented AFSCs were ranked according to their importance. To achieve this, five experienced experts were chosen through purposive sampling. Due to confidentiality reasons, the identities of the experts and companies involved in this study are not disclosed. Table 3 provides company and respondent profiles. The I4.0-S-CE drivers, derived from the literature and consisting of three main drivers with eighteen sub-drivers, were approved by experts and listed as shown in Table 4.

[INSERT TABLE 3 HERE]

[INSERT TABLE 4 HERE]

FBWM results

In the study's first phase, the weights of the I4.0-S-CE drivers to achieve SDGs-oriented AFSCs were determined using the FBWM. The FBWM was chosen to determine the relative importance of I4.0-S-CE drivers due to its advantages, including more consistency and fewer pairwise comparisons. FBWM was applied using the following steps.

Step1. Identify the best (C_B) and worst (C_W) drivers. The team carefully evaluated the drivers and determined which criteria represented the best and worst outcomes for each alternative.

Step 2. Use a linguistic scale for pairwise comparisons of the drivers. The linguistic scale shown in Table 2 was used for the pairwise comparisons of the criteria.

Step 3. Obtain the pairwise comparisons of C_B and C_W with other drivers. Pairwise comparisons of C_B and C_W with other drivers were conducted using the linguistic terms, which were then transformed into corresponding TFNs as shown in Table 2.

Step 4. Calculate the normalized weights of drivers. The mathematical model of FBWM is then implemented based on these TFNs. For example, Expert 1 (E1) identifies the BO and OW vectors of I4.0 drivers as follows:

$\tilde{A}_B$= [(0.67,1,1.5), (1.5,2,2.5), (1,1,1)] and $\tilde{A}_W$ = [(1,1,1), (0.67,1,1.5), (0.67,1,1.5)]. Then, the FBWM is constructed by applying Eq (19).

$$
\begin{aligned}
&\min \tilde{\xi} \\
&s.t. \\
&l3 - 0.67u1 \leq \tilde{\xi} * u1; \;\; l3 - 0.67 * u1 \geq -\tilde{\xi} * u1 \qquad (19) \\
&m3 - 1m1 \leq \tilde{\xi} * m1; \;\; m3 - 1 * m1 \geq -\tilde{\xi} * m1 \\
&u3 - 1.5l1 \leq \tilde{\xi} * l1; \;\; u3 - 1.5 * l1 \geq -\tilde{\xi} * l1 \\
&l3 - 1.5u2 \leq \tilde{\xi} * u2; \;\; l3 - 1.5 * u2 \geq -\tilde{\xi} * u2 \\
&m3 - 2m2 \leq \tilde{\xi} * m2; \;\; m3 - 2 * m2 \geq -\tilde{\xi} * m2 \\
&u3 - 2.5l2 \leq \tilde{\xi} * l2; \;\; u3 - 2.5 * l2 \geq -\tilde{\xi} * l2 \\
&l2 - 0.67u1 \leq \tilde{\xi} * u1; \;\; l2 - 0.67 * u1 \geq -\tilde{\xi} * u1 \\
&m2 - 1m1 \leq \tilde{\xi} * m1; \;\; m2 - 1 * m1 \geq -\tilde{\xi} * m1
\end{aligned}
$$

$u2 - 1.5l1 \leq \tilde{\xi} * l1; \quad u2 - 1.5 * l1 \geq -\tilde{\xi} * l1$

$l1 + 4m1 + u1 + l2 + 4m2 + u2 + l3 + 4m3 + u3 = 6$

$l1 \leq m1;\ l2 \leq m2;\ l3 \leq m3;$

$m1 \leq u1;\ m2 \leq u2;\ m3 \leq u3;$

$l1 > 0;\ l2 > 0;\ l3 > 0$

$\tilde{\xi} \geq 0$

The fuzzy weights of the I4.0 drivers, reflecting the preferences of Expert 1 (E1), were calculated using Lingo 19.0 software and are as follows: $\tilde{w}_1^*$ = (0.265, 0.317, 0.521); $\tilde{w}_2^*$ = (0.210, 0.232, 0.326); $\tilde{w}_3^*$ = (0.402, 0.402, 0.468). Also, *CI* is $\tilde{\xi}$=0.268. By calculating the *CR* as 0.268/5.29=0.051, it is concluded that the obtained results are acceptable (*CR* < 0.10). The linguistic evaluations, fuzzy, and crisp weights of I4.0-S-CE drivers are given in Tables 5-7. The global weights of I4.0-S-CE drivers are shown in Table 8.

[INSERT TABLE 5 HERE]

[INSERT TABLE 6 HERE]

[INSERT TABLE 7 HERE]

[INSERT TABLE 8 HERE]

FWASPAS results

In the study's second phase, the agricultural SDGs' final ranking results were determined using the FWASPAS method. The FWSPAS method is preferred because it combines the Weighted Sum Model (WSM) and Weighted Product Model (WPM) steps to consider the experts' preferences comprehensively. Thus, it enables the integration of the experts' evaluations more rationally and effectively. FWASPAS was applied using the following steps.

Step 5. Calculate the weighted normalized fuzzy decision matrix. The fuzzy linguistic variables given in Table 9 were used to obtain the experts' linguistic preferences regarding the SDGs, as shown in Table 10. Then, the weighted normalized WSM and WPM values were calculated for each alternative using Eqs (10) to (12) and presented in Tables 11 and 12.

Step 6. Calculate the optimality function values for alternatives. This step involves calculating the optimality function values of WSM and WPM for each alternative and applying the center of area method for defuzzification using Eqs (13) to (16).

Step 7. Determine the integrated utility function values of alternatives. The integrated utility function values of each alternative are obtained using Eqs (17) and (18).

Step 8. Determine the ranking results of alternatives. The final step is to rank the alternatives in descending order based on their K_i values as seen in Table 13.

[INSERT TABLE 9 HERE]

[INSERT TABLE 10 HERE]

[INSERT TABLE 11 HERE]

[INSERT TABLE 12 HERE]

[INSERT TABLE 13 HERE]

Validation of the results

The validation phase involves comparing the results with those obtained using the FTOPSIS, FSAW, and FARAS methods and conducting a one-at-a-time sensitivity analysis (see the Appendix).

Comparison with FTOPSIS, FARAS, and FSAW methods

The study's results were compared with the results of TOPSIS (Büyüközkan & Çifçi, 2012), SAW (Chou et al., 2008), and ARAS (Zavadskas & Turskis, 2010) methods in fuzzy environment. The data used to compare these methods is presented in the Appendix. While TOPSIS and SAW rank alternatives using calculated distance to an ideal reference point, ARAS ranks them by comparing to the one with the best utility. These methods allow for their combined use to produce more balanced and robust rankings. At this stage, the weights of the criteria were accepted as the same as in FBWM, and then the results of the SDGs were recalculated using each of the other methods in a fuzzy environment. As shown in Figure 2, SDG12 is ranked first in all methods. This indicates that the results obtained through different decision-making methods are generally consistent, robust, and reliable.

[INSERT FIGURE 2 HERE]

One-at-a-time sensitivity analysis

As seen in Figure 3, one-at-a-time sensitivity analysis was performed by considering variations in criteria weights. Firstly, by changing the weights of the I4.0 criteria according to the sustainability criteria, SDG12 emerged as the best choice in all possible variations. Secondly, after adjusting the weights of the I4.0 criteria according to CE criteria, SDG12 remained the preferred choice in all scenarios. Thirdly, after adjusting the weights of the sustainability criteria according to CE criteria, SDG12 maintained the highest position in all situations. Furthermore, when the weight of each main criterion was sequentially increased while the others remained proportionally constant, it can be observed that SDG2, SDG7, and SDG15 occupied the second positions in all scenarios. Therefore, SDG12, SDG2, SDG7, and SDG15 show good stability, confirming the robustness and reliability of the study's main findings.

[INSERT FIGURE 3 HERE]

Discussion

Numerous studies in the literature have examined the relationships between I4.0-S-CE. I4.0 has been found to have a positive impact on CE (Lopes de Sousa Jabbour et al., 2018; P. Kumar et al., 2021), including CE practices (Abdul-Hamid et al., 2021; Kamble & Gunasekaran, 2023), circular supply chains (Kayikci et al., 2022a), and CE performance (Zhang et al., 2022; Agrawal et al., 2023). Similarly, other studies have explored the relationships between I4.0 and sustainability/SDGs (Luthra et al., 2019; Bag et al., 2021a; Gupta et al., 2021), as well as CE and sustainability/SDGs (Rodriguez-Anton et al., 2019; Schroeder et al., 2019; Corona et al., 2019; Dantas et al., 2021; Belmonte-Ureña et al., 2021). The first group of studies focuses on the impact of I4.0 on CE, while the second group investigates the effects of CE on sustainability and SDGs.

There is a lack of studies in the literature investigating the relationships between I4.0-S-CE drivers and agricultural SDGs in the context of transitioning to SDGs-oriented AFSCs. Thus, this study offers valuable insights into identifying the drivers that support the development of SDGs-oriented AFSCs in developing countries. Furthermore, determining the significance and impact of these drivers on agricultural SDGs will help managers and policymakers improve food security, reduce waste, and alleviate pressure on natural resources. Additionally, the issue of uncertainty and ambiguity in assessing the connection between the drivers of I4.0-S-CE nexus and ranking the agricultural SDGs was addressed using fuzzy decision-making methods. Differing from the literature, the drivers' weights were determined using FBWM and SDGs ranked through FWASPAS. Moreover, comparison analysis and one-at-a-time sensitivity analysis were employed for validation. The study findings indicate that sustainability (C2) emerges as the most significant driver, followed by CE (C3) and I4.0 (C1).

Sustainability drivers

Sustainability drivers are ranked in the order of economic sustainability, social sustainability, and the achievement of standards and SDGs. Innovative business models, environmental sustainability, and competitiveness follow them. The study's findings illustrated that AFSCs provide sustainability through closed-loop systems, which reduce the need for primary resources and minimize overall waste, in line with the results of Sgarbossa & Russo (2017) and Kirchherr et al. (2016). As noted by Islam & Zheng (2024), CE's reuse, recovery, and recycling practices play a significant role in achieving the SDGs, conserving resources, reducing waste and pollution, and promoting economic and social sustainability. Furthermore, supporting the results of Lewandowski (2016) and Boons & Lüdeke-Freund (2013), the design of circular business models, along with incorporating renewable sources and CE principles, enhances competitiveness and fosters sustainable development.

CE drivers

CE drivers are ranked in order of importance as resource efficiency, supply chain connectivity, and regulatory compliance. These are followed by waste and emission reduction, traceability and transparency, and stakeholders' rights. Therefore, CE improves resource efficiency and productivity in circular agri-food production, as highlighted by Zhu et al. (2019). Such initiatives also improve the circularity approach that supports reducing food waste and emissions, developing production traceability, and increasing stakeholders' rights (Zhang et al., 2022). In line with the findings of Islam & Zheng (2024), CE practices are critical to the sustainable development of agri-food systems, the eradication of hunger (SDG2), the use of renewable energy (SDG7), and the adoption of sustainable consumption (SDG12). Also, adopting CE drivers to develop SDGs-oriented AFSCs contributes to the eradication of poverty (SDG1) and hunger (SDG2), promoting good health (SDG3) and responsible consumption (SDG12). It also helps in providing renewable resources such as water (SDG6) and energy (SDG7), as well as protecting the climate (SDG13) and terrestrial ecosystems (SDG15) (Barros et al., 2020; Zhang et al., 2022; Esposito et al., 2020; Negra et al., 2020).

I4.0 drivers

BDA, cloud computing, and IoT stand out as the most important drivers of I4.0. These are followed by sensors and robotics, blockchain, and AI. According to Kshetri (2014) and Song et al. (2017), BDA improves resource efficiency and decision-making performance by facilitating the capture, analysis, and sharing of agricultural data. In line with the findings of Lezoche et al. (2020)'s study, the integration of wireless networks, cloud computing, and IoT provides additional agricultural data related to water, soil, humans, and animals. Furthermore, Zhao et al. (2019) explained that AFSCs should adopt blockchain technology. In line with the findings of Wolfert et al. (2017), these innovations enhance transparency, automation, and autonomous operations throughout the AFSCs. Furthermore, the study's findings, aligning with Abbate et al. (2023), suggested that integrating sensors, RFID, remote sensing, and AI contributes to achieving real-time traceability and operational efficiency, thereby addressing the inherent vulnerabilities of AFSCs. Thus, I4.0 drivers support SDGs by increasing productivity, reducing food loss and waste, and ensuring access to safe and nutritious food.

Conclusions

This research contributes significantly to addressing literature gaps regarding the required I4.0-S-CE drivers for transition to SDGs-oriented AFSCs in developing countries, as well as the ranking of agricultural SDGs aligned with AFSCs. Three main drivers and eighteen sub-drivers were identified based on a literature review and expert opinions. The FBWM method was used to determine the weights of the drivers, and the FWASPAS method was used to rank the agricultural SDGs. To validate the study's findings, a comparison analysis was performed using the FTOPSIS, FARAS, and FSAW methods, along with a one-at-a-time sensitivity analysis.

Considering the importance weights of drivers, sustainability was the highest weight, followed by CE and I4.0. Furthermore, resource efficiency, economic and social sustainability, and the achievement of standards and SDGs were identified as the most important sub-drivers. Thus, effective use of resources was assessed as the most important key to meeting the agricultural needs of developing countries. Improving resource efficiency drives economic growth, environmental protection and social well-being in developing countries. SDGs-oriented AFSCs support agricultural and rural development by employing circular production methods. Supporting smallholder farmers with technology, financial aid, and management can reduce costs, increase productivity, and improve food security and quality. Thus, collaboration between government agencies, farmers, distributors, cooperatives, and consumers is crucial for achieving the SDGs.

Another contribution of the study is the ranking of agricultural SDGs aligned with AFSCs in developing countries. The study results revealed that sustainable consumption and production (SDG12) is the most crucial target in a developing country like Turkey. However, achieving SDG2, SDG7, and SDG15 will guide developing countries towards goals of zero hunger, renewable and clean energy, and ecosystem protection. Furthermore, striving for other agricultural SDGs, including poverty eradication (SDG1), improved quality of life (SDG3), water resource protection (SDG6), and climate change mitigation (SDG13), is also essential. The study provides valuable insights for practitioners to align their operations with the agricultural SDGs and to promote I4.0-S-CE practices in AFSCs. It also guides policymakers to formulate policies that support the achievement of the SDGs-oriented AFSCs.

Implications for Practice

The increasing number of emergencies, crises, and climate change issues has created significant environmental, social, and economic problems. SDGs-oriented AFSCs have great potential in dealing with these problems. They can provide access to safe and nutritious food, reduce waste and emissions, conserve biodiversity, and promote the sustainable use of natural resources. Therefore, managers should consider the integrated contribution of I4.0-S-CE drivers in transitioning to SDGs-oriented AFSCs to meet developing countries' current and future needs.

The study has identified that SDG1, SDG2, SDG3, SDG6, SDG7, SDG12, SDG13, and SDG15 are directly or indirectly related to the agricultural SDGs. Thus, managers must develop strategies that align with the agricultural SDGs. By considering resource efficiency, managers can actively contribute to responsible consumption and production (SDG12). The SDGs report emphasizes the achievement of SDG12 in AFSCs to reduce the growing dependence on natural resources (UN, 2022). Furthermore, it contributes to reducing food loss and waste, which reached 13.3 percent in 2020 (UN, 2022), and the targets related to poverty (SDG1), hunger (SDG2), and good health (SDG3). As of 2021, 1 in 10 people worldwide is at risk of hunger, and about one-third of the global population lacks sufficient access to safe and nutritious food (Negra et al., 2020). Practitioners should address hunger (SDG2) by increasing regular access to adequate food, eliminating food insecurity and malnutrition, and promoting the participation of smallholder farmers in SDGs-oriented AFSCs, especially in developing countries. Moreover, promoting renewable and clean energy (SDG7) and addressing climate change and its impacts (SDG13) are crucial for promoting healthy ecosystems (SDG15), conserving biodiversity, reducing carbon emissions, and protecting water resources (SDG6).

Implications for Policy

The agriculture sector serves as an engine for economic growth in developing countries. However, environmental, economic, and social issues stemming from this sector hinder the achievement of SDGs-oriented AFSCs. Policymakers should develop strategies and regulations that involve all stakeholders, including farmers, cooperatives, and consumers, to achieve the agricultural SDGs. It is also important to raise awareness about natural resource use, promote precision and smart agriculture, improve food safety and access, and enhance transparency and traceability. Therefore, the integrated contribution of I4.0-S-CE drivers will play a key role in achieving the SDGs-oriented AFSCs in developing countries. As a result, SDGs-oriented AFSCs promote a system focused on food security, sustainable agriculture, environmental conservation, and the health and well-being of future generations.

Limitations and Future Work

AFSCs in developing countries acquire limited benefits from I4.0-S-CE drivers due to the insufficiency of technological infrastructure, lack of cooperation between stakeholders, and limited awareness about sustainability, circularity, and regulatory issues in these regions. An important consideration is that the benefits arising from these drivers will increase as digitalization and sustainability issues improve in these countries. Furthermore, incorporating I4.0-S-CE drivers that promote sustainable and circular agriculture can help develop AFSCs aligned with the SDGs. In future studies, the I4.0-S-CE drivers that enable the development of SDGs-oriented AFSCs can be defined in more detail. Furthermore, researchers can test the validity of this study by adapting the proposed drivers to other industries in emerging economies.

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TABLES

Table 1 The selected studies on the relationships between I4.0-S-CE and the SDGs from 2017 to June 2023

Authors	Analytical methods	Key features	Industry
Zisopoulos et al., 2017	Entropy	Proposed a framework for designing a resource-efficient agri-food sector that contributes to the achievement of the SDGs.	Food supply chain
Stock et al., 2018	Qualitative assessment	Assessed the ecological and social value of Industry 4.0 towards SDGs.	Cube production
Schroeder et al., 2019	Literature review and qualitative heuristic research	Identified the relevant CE practices that contribute to the implementation of multiple SDGs.	Food supply chain
Rodriguez-Anton et al., 2019	Statistical evaluation	Analysed the relationships between the CE initiatives and the SDGs.	European Union countries
Corona et al., 2019	Life cycle analysis	Evaluated the role of circularity indicators for SDGs through CE.	Qualitative assessment
Belmonte-Ureña et al., 2021	Bibliometric analysis	Investigated the impact of CE, degrowth, and green growth on the achievement of SDGs.	The most productive countries
Dantas et al., 2021	Literature review	Proposed the importance of CE practices and I4.0 combination towards achieving the SDGs.	Qualitative assessment
Karuppiah et al., 2021	Grey DEMATEL, Fuzzy COPRAS	Analysed the inhibitors for CE adoption and proposed several implications for SDGs.	Leather industry
Mina et al., 2021	Fuzzy AHP and Fuzzy TOPSIS	Identified economic and circular criteria for evaluating circular suppliers to achieve SDGs.	Petrochemical industry
Nara et al., 2021	Fuzzy TOPSIS	Investigated the impact of I4.0 technologies on sustainable development.	Plastic industry
Nikolaou & Tsagarakis, 2021	Literature review	Focused on CE and sustainability, which emphasizes SDGs.	Industrial ecology
Kayikci et al., 2022a	BWM and TOPSIS	Analysed the drivers of smart circular supply chain criteria for attaining the SDGs.	Textile industry
Bai et al., 2022	DEMATEL and a linear model	Explored the impact of I4.0 technologies on the achievement of SDGs through a CE approach.	Electronics industry
Agrawal et al., 2021	Bibliometric and network analysis	Proposed the integration of I4.0 and CE to improve the design of product-service systems for sustainable societies.	Logistic and supply chain applications
Lahane & Kant, 2022	Pythagorean Fuzzy AHP, Pythagorean Fuzzy COPRAS	Examined the CE practices that contribute to the achievement of the various SDGs for circular supply chains.	Manufacturing industry
Popkova et al., 2022	Statistical evaluation	Discussed the social and economic policy implications of digital technology development on sustainable development.	Developed and developing countries
Dwivedi et al., 2022	Grey DEMATEL	Identified potential challenges to I4.0 and CE interaction for the implementation of sustainable footwear production.	Footwear production
Di Maria et al., 2022	Partial Least Squares -Structural Equation Model	Analysed the mediating role of supply chain integration in I4.0 and CE nexus.	Manufacturing industry
Alam et al., 2023	Fuzzy TISM, Fuzzy MICMAC	Assessed the drivers of Agriculture 4.0 to ensure sustainability and achieve the relevant SDGs.	Food supply chain
Abbate et al., 2023	Literature review	Analysed the current state of I4.0 and sustainability in the agri-food industry that contribute to the achievement of several SDGs.	Agri-food industry
De Mattos Nascimento et al., 2023	Literature review, Fuzzy Delphi	Proposed novel classification of the interrelationships between I4.0 and CE principles by establishing guideline in assisting with practical applications in supply chains.	Qualitative assessment

Table 2 Linguistic scale and CI

Linguistic terms	Corresponding TFNs	Consistency index (CI)
Equally important (EI)	(1, 1, 1)	3.00
Weakly important (WI)	(2/3, 1, 3/2)	3.80
Fairly important (FI)	(3/2, 2, 5/2)	5.29
Very important (VI)	(5/2, 3, 7/2)	6.69
Absolutely important (AI)	(7/2, 4, 9/2)	8.04

Table 3 Company and respondent profiles

Experts (E)	**Company products**	**Respondent profiles**	**Years**	**Company details**
E1	Olive oil and other cooking oils	Logistics Manager	12 years	Workers: 100-500 Sales: $45 million
E2	Rice, pasta, legumes, and other dry food products	Production Manager	14 years	Workers: >500-750 Sales: $250 million
E3	Cakes, pastries, cookies, biscuit products, and other flour-based products	IT/Software Manager	8 years	Workers: 500-750 Sales: $700 million
E4	Pickles, canned vegetables, sauces, and other canned goods	Supply Chain Manager	6 years	Workers: 100-500 Sales: $30 million
E4	Fruit juice, soda, and other beverages	Operations Manager	15 years	Workers: <100 Sales: $20 million

Table 4 List of selected drivers for I4.0-S-CE towards achieving SDGs

Drivers/Criteria	Description	References
C1. I4.0		
C11. Cloud computing	Cloud computing allows farmers to collect and store large amounts of smart and precise farming data. Intelligent applications are then used to derive valuable insights regarding irrigation, fertilisation, and other aspects of farming.	Lopes de Sousa Jabbour et al., 2018; Lezoche et al., 2020; Alam et al., 2023; Zhao et al., 2019
C12. Sensors and robotics	Sensors and robotics are used to monitor various farming activities.	Wolfert et al., 2017; Nara et al., 2021; Alam et al., 2023
C13. IoT	Enables crop identification and improves real-time tracking for agricultural challenges such as temperature, humidity, pest disease, water, soil, and waste issues to improve productivity.	Wolfert et al., 2017; Lopes de Sousa Jabbour et al., 2018; Nara et al., 2021; P. Kumar et al., 2021; Zhao et al., 2019; Kayikci et al., 2020
C14. Blockchain	Provides transparency, traceability, and security from farm to fork for AFSCs.	Kshetri, 2014; Lezoche et al., 2020; Zhao et al., 2019; Kayikci et al., 2020; Erol et al., 2022
C15. Big data analytics (BDA)	Contributes to real-time decision-making related to yield, price, weather, crops, harvesting and other agricultural issues.	Kshetri, 2014; Song et al., 2017; Belaud et al., 2019; Nara et al., 2021; Wolfert et al., 2017; Alam et al., 2023
C16. Artificial intelligence (AI)	Supports decision-making in several agricultural issues such as pest-disease management, water saving, soil conservation, irrigation, and robot guidance.	Nara et al., 2021; Lezoche et al., 2020; Alam et al., 2023
C2. Sustainability		
C21. Economic sustainability	Focuses on the accessibility, affordability, and economic value of products.	Schmitt et al., 2016; Kamble et al., 2020; Kamble & Gunasekaran, 2023
C22. Environmental sustainability	Encompasses concerns about pollution, greenhouse gas emissions, resource use, loss of biodiversity, food loss and waste.	Schmitt et al., 2016; Kamble et al., 2020; Kamble & Gunasekaran, 2023; Kusumowardani et al., 2022
C23. Social sustainability	Covers interactions and relationships related to the social, health and ethical issues between all stakeholders.	Schmitt et al., 2016; Kamble et al., 2020; Corona et al., 2019; Kamble & Gunasekaran, 2023
C24. Innovative business models	Include public-private partnerships and farmer cooperatives, along with technologies and practices such as crop varieties, ecological practices, biotechnologies, and financial instruments.	Boons & Lüdeke-Freund, 2013; Lewandowski, 2016; Bocken et al., 2018; FAO, 2018; Schroeder et al., 2019; Barros et al., 2020
C25. Competitiveness	Embracing I4.0, smart and precise farming, and CE practices is crucial for achieving competitiveness. These practices involve optimising resource utilisation, reducing waste and emissions, and enhancing overall productivity.	Kamble et al., 2020; Barros et al., 2020; Bai et al., 2020; Kusumowardani et al., 2022
C26. Achievement of standards and SDGs	Agricultural practices should be aligned with standards and SDGs to address key challenges such as food security and quality, economic and environmental sustainability, and social well-being.	Schroeder et al., 2019; Barros et al., 2020; Bai et al., 2020; Dantas et al., 2021; Karuppiah et al., 2021
C3. CE		
C31. Resource efficiency	Resource efficiency aims to design a restorative and regenerative system that eliminates food loss and waste in AFSCs.	Sgarbossa & Russo, 2017; Zhao et al., 2019; Barros et al., 2020; Kamble et al., 2020; Esposito et al., 2020; Abbate et al., 2023
C32. Waste and emissions reduction	CE reduces greenhouse gas emissions in AFSCs through the circulation of raw materials and agricultural waste recovery.	Song et al., 2017; Sgarbossa & Russo, 2017; Corona et al., 2019; Barros et al., 2020; Annosi et al., 2020; Dantas et al., 2021; Kusumowardani et al., 2022; Abbate et al., 2023
C33. Supply chain connectivity	Legislators, livestock farmers, cooperatives, crop farmers, distributors, and consumers must cooperate from farm to fork.	Sgarbossa & Russo, 2017; Barros et al., 2020; Negra et al., 2020; Kayikci et al., 2022a
C34. Traceability and transparency	Traceability and transparency facilitate the movement of food products and the sharing of information among all stakeholders, aiming to develop circular production systems for AFSCs.	Kayikci et al., 2020; Kamble et al., 2020; Erol et al., 2022
C35. Legal compliance	Legal compliance includes environmental regulations, food security and quality standards, farming regulations, trade, and export laws.	Kayikci et al., 2020; Karuppiah et al., 2021; Lahane & Kant, 2022
C36. Stakeholders' rights	Stakeholders' rights encompass various issues, such as access to safe and nutritious food, employees' rights, sustainable farming practices, sustainable management of natural resources, and involvement in decision-making processes.	Kayikci et al., 2020; Kamble et al., 2020; Lahane & Kant, 2022

Table 5 Linguistic evaluations of I4.0-S-CE drivers determined by experts

Experts	BO vector of the drivers							OW vector of the drivers						
	Best	C1	C2	C3				Worst	C1	C2	C3			
E1	*C3*	*WI*	*FI*	*EI*				*C1*	*EI*	*WI*	*WI*			
E2	C3	FI	VI	EI				C2	FI	EI	VI			
E3	C3	AI	WI	EI				C1	EI	FI	AI			
E4	C2	FI	EI	AI				C1	EI	FI	WI			
E5	C2	VI	EI	AI				C1	EI	VI	WI			
	BO vector of the I4.0 driver							**OW vector of the I4.0 driver**						
	Best	C11	C12	C13	C14	C15	C16	Worst	C11	C12	C13	C14	C15	C16
E1	C11	EI	VI	FI	WI	AI	AI	C16	AI	WI	FI	VI	WI	EI
E2	C12	VI	EI	WI	AI	WI	FI	C14	WI	AI	VI	EI	VI	FI
E3	C15	FI	FI	WI	VI	EI	WI	C14	WI	FI	WI	EI	VI	WI
E4	C11	EI	FI	VI	VI	FI	AI	C16	AI	WI	WI	FI	WI	EI
E5	C15	FI	FI	AI	WI	EI	FI	C13	FI	FI	EI	VI	AI	FI
	BO vector of the CE driver							**OW vector of the CE driver**						
	Best	C21	C22	C23	C24	C25	C26	Worst	C21	C22	C23	C24	C25	C26
E1	C21	EI	AI	FI	AI	WI	WI	C24	AI	WI	FI	EI	AI	VI
E2	C22	FI	EI	VI	FI	AI	FI	C25	FI	AI	FI	FI	EI	AI
E3	C23	VI	FI	EI	FI	WI	VI	C26	WI	FI	VI	FI	VI	EI
E4	C21	EI	AI	WI	WI	FI	WI	C25	FI	WI	FI	WI	EI	WI
E5	C24	WI	WI	WI	EI	AI	VI	C25	VI	FI	VI	AI	EI	FI
	BO vector of the sustainability driver							**OW vector of the sustainability driver**						
	Best	C31	C32	C33	C34	C35	C36	Worst	C31	C32	C33	C34	C35	C36
E1	C31	EI	AI	FI	AI	VI	VI	C32	AI	EI	FI	FI	FI	WI
E2	C34	WI	WI	WI	EI	FI	FI	C33	FI	WI	EI	WI	WI	WI
E3	C35	FI	FI	WI	AI	EI	VI	C34	WI	WI	AI	EI	AI	WI
E4	C31	EI	AI	FI	VI	WI	VI	C32	AI	EI	VI	FI	FI	WI
E5	C31	EI	FI	AI	AI	VI	VI	C33	AI	WI	EI	WI	WI	WI

Table 6 Fuzzy and crisp relative weights of I4.0-S-CE drivers

Drivers	E1	E2	E3	E4	E5	Weight
C1	(0.265, 0.317, 0.521)	(0.222, 0.308, 0.340)	(0.134, 0.145, 0.145)	(0.203, 0.243, 0.304)	(0.170, 0.195, 0.230)	0.246
C2	(0.210, 0.232, 0.326)	(0.149, 0.172, 0.172)	(0.278, 0.355, 0.395)	(0.608, 0.608, 0.608)	(0.646, 0.646, 0.646)	0.403
C3	(0.402, 0.402, 0.468)	(0.440, 0.551, 0.551)	(0.442, 0.515, 0.542)	(0.122, 0.135, 0.203)	(0.134, 0.150, 0.202)	0.351
CR	*CR = 0.051*	*CR = 0.031*	*CR = 0.056*	*CR = 0.062*	*CR = 0.038*	

Table 7 Fuzzy and crisp relative weights of I4.0-S-CE drivers

Drivers	E1	E2	E3	E4	E5	Weight
C11	(0.232, 0.232, 0.286)	(0.105, 0.116, 0.151)	(0.198, 0.206, 0.229)	(0.256, 0.269, 0.397)	(0.118, 0.150, 0.157)	0.201
C12	(0.125, 0.129, 0.165)	(0.255, 0.255, 0.282)	(0.108, 0.115, 0.146)	(0.115, 0.115, 0.115)	(0.118, 0.150, 0.166)	0.155
C13	(0.168, 0.192, 0.238)	(0.202, 0.202, 0.228)	(0.157, 0.157, 0.157)	(0.162, 0.162, 0.162)	(0.069, 0.069, 0.069)	0.158
C14	(0.274, 0.274, 0.310)	(0.053, 0.053, 0.062)	(0.083, 0.091, 0.112)	(0.089, 0.089, 0.113)	(0.186, 0.221, 0.255)	0.148
C15	(0.072, 0.072, 0.085)	(0.202, 0.202, 0.228)	(0.198, 0.261, 0.350)	(0.256, 0.256, 0.259)	(0.225, 0.268, 0.319)	0.214
C16	(0.072, 0.072, 0.085)	(0.143, 0.149, 0.175)	(0.157, 0.157, 0.157)	(0.073, 0.083, 0.100)	(0.118, 0.150, 0.166)	0.123
CR	*CR = 0.039*	*CR = 0.037*	*CR = 0.084*	*CR = 0.062*	*CR = 0.027*	
Drivers	**E1**	**E2**	**E3**	**E4**	**E5**	**Weight**
C21	(0.267, 0.267, 0.296)	(0.118, 0.118, 0.135)	(0.077, 0.089, 0.099)	(0.283, 0.283, 0.283)	(0.143, 0.179, 0.225)	0.189
C22	(0.062, 0.062, 0.084)	(0.293, 0.315, 0.368)	(0.114, 0.159, 0.176)	(0.056, 0.062, 0.097)	(0.141, 0.177, 0.225)	0.157
C23	(0.105, 0.119, 0.155)	(0.130, 0.130, 0.130)	(0.227, 0.284, 0.284)	(0.135, 0.178, 0.224)	(0.143, 0.179, 0.225)	0.177
C24	(0.071, 0.071, 0.071)	(0.116, 0.118, 0.135)	(0.114, 0.159, 0.176)	(0.135, 0.178, 0.224)	(0.277, 0.277, 0.290)	0.160
C25	(0.225, 0.261, 0.296)	(0.071, 0.071, 0.071)	(0.203, 0.247, 0.258)	(0.107, 0.112, 0.135)	(0.073, 0.073, 0.073)	0.152
C26	(0.163, 0.203, 0.270)	(0.201, 0.237, 0.272)	(0.077, 0.089, 0.089)	(0.135, 0.178, 0.224)	(0.071, 0.106, 0.143)	0.163
CR	*CR = 0.039*	*CR = 0.084*	*CR = 0.031*	*CR = 0.074*	*CR = 0.070*	
Drivers	**E1**	**E2**	**E3**	**E4**	**E5**	**Weight**
C31	(0.404, 0.404, 0.404)	(0.170, 0.292, 0.292)	(0.100, 0.120, 0.140)	(0.276, 0.282, 0.361)	(0.370, 0.394, 0.394)	0.296
C32	(0.078, 0.086, 0.102)	(0.108, 0.194, 0.194)	(0.100, 0.120, 0.140)	(0.073, 0.080, 0.094)	(0.134, 0.161, 0.190)	0.126
C33	(0.151, 0.151, 0.186)	(0.108, 0.146, 0.146)	(0.280, 0.294, 0.294)	(0.186, 0.196, 0.293)	(0.097, 0.111, 0.121)	0.182
C34	(0.103, 0.115, 0.143)	(0.146, 0.194, 0.198)	(0.072, 0.083, 0.089)	(0.116, 0.116, 0.142)	(0.096, 0.102, 0.102)	0.122
C35	(0.115, 0.115, 0.143)	(0.070, 0.117, 0.126)	(0.272, 0.294, 0.294)	(0.193, 0.197, 0.224)	(0.114, 0.114, 0.125)	0.168
C36	(0.110, 0.110, 0.129)	(0.070, 0.117, 0.126)	(0.089, 0.089, 0.121)	(0.089, 0.089, 0.108)	(0.117, 0.117, 0.130)	0.106
CR	*CR = 0.084*	*CR = 0.063*	*CR = 0.056*	*CR = 0.070*	*CR = 0.056*	

Table 8 The global weights of the I4.0-S-CE drivers

Drivers	Weights	Sub-drivers/criteria	Local weights	Global weights	Rank
C1. I4.0	0.246	C11	0.201	0.049	11
		C12	0.155	0.038	15
		C13	0.158	0.039	14
		C14	0.148	0.036	17
		C15	0.214	0.053	10
		C16	0.123	0.030	18
C2. Sustainability	0.403	C21	0.189	0.076	2
		C22	0.157	0.063	7
		C23	0.177	0.071	3
		C24	0.160	0.064	5
		C25	0.152	0.061	8
		C26	0.163	0.066	4
C3. CE	0.351	C31	0.296	0.104	1
		C32	0.126	0.044	12
		C33	0.182	0.064	6
		C34	0.122	0.043	13
		C35	0.168	0.059	9
		C36	0.106	0.037	16

Table 9 Fuzzy linguistic variables

Linguistic variables	TFNs
Very low (VL)	(1, 1, 3)
Low (L)	(1, 3, 5)
Medium (M)	(3, 5, 7)
High (H)	(5, 7, 9)
Very High (VH)	(7, 9, 9)

Table 10 The experts' linguistic preferences

	SDG1					SDG2					SDG3					SDG6				
	E1	**E2**	**E3**	**E4**	**E5**	**E1**	**E2**	**E3**	**E4**	**E5**	**E1**	**E2**	**E3**	**E4**	**E5**	**E1**	**E2**	**E3**	**E4**	**E5**
C11	VL	M	M	M	M	L	M	L	L	L	M	VL	VL	VL	VL	H	L	L	L	L
C12	M	H	M	M	M	H	H	H	H	H	M	H	L	H	H	M	M	M	VL	VL
C13	VL	H	L	L	L	L	M	M	M	M	M	H	M	M	M	H	M	VH	VH	VH
C14	M	M	L	L	L	M	M	H	H	H	H	VL	L	L	L	VL	H	VL	VL	VL
C15	M	M	M	M	M	H	M	M	M	M	M	M	VH	VH	VH	H	L	M	M	M
C16	M	M	L	L	L	H	M	L	L	L	L	M	L	L	L	L	M	M	M	M
C21	L	VH	L	L	L	L	VH	H	H	H	M	VH	M	L	M	VL	VH	L	M	L
C22	VH	H	VH	VH	VH	H	L	H	H	H	H	L	H	H	H	L	VH	VL	VL	VL
C23	L	H	H	H	H	VL	M	VH	VH	VH	L	H	H	H	H	M	M	M	M	M
C24	VL	H	H	H	H	H	M	VL	VL	VL	VL	H	VL	VL	VL	L	M	M	M	M
C25	H	H	H	H	H	H	H	M	M	M	H	H	VH	VH	VH	VL	H	VL	VL	VL
C26	M	M	H	H	H	M	M	H	H	H	M	M	H	H	H	M	M	M	L	L
C31	L	H	L	L	L	H	H	L	L	L	H	H	M	M	M	H	H	VL	M	VL
C32	VH	VH	VH	VH	VH	VH	VH	H	H	H	H	VH	H	H	H	L	VH	L	L	L
C33	VH	VH	VH	VH	VH	H	VH	H	H	H	M	VH	M	M	M	H	VH	H	H	H
C34	VL	H	VL	VL	VL	H	H	H	H	H	VL	H	VL	VL	VL	VL	M	VL	VL	VL
C35	H	M	H	H	H	H	M	H	H	H	H	M	H	H	H	VL	M	M	VL	VL
C36	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
	SDG7					**SDG12**					**SDG13**					**SDG15**				
	E1	**E2**	**E3**	**E4**	**E5**	**E1**	**E2**	**E3**	**E4**	**E5**	**E1**	**E2**	**E3**	**E4**	**E5**	**E1**	**E2**	**E3**	**E4**	**E5**
C11	M	M	M	M	M	M	M	H	M	M	M	M	H	M	M	VH	VL	VH	M	M
C12	M	L	H	H	H	VL	L	H	M	H	L	M	VH	M	H	M	VL	VH	H	H
C13	M	VL	M	H	M	M	M	VH	H	VH	M	M	M	M	M	H	VL	VH	VH	VH
C14	H	M	H	H	H	VL	M	VH	H	M	L	M	H	H	VH	M	L	VH	H	M
C15	M	M	VH	VH	H	H	M	M	VH	M	M	VL	VH	VH	VH	H	H	M	VH	VH
C16	L	L	M	L	H	VL	VL	M	M	M	L	VL	M	L	VH	M	VH	M	M	VH
C21	L	VL	VH	M	H	VL	VH	VL	M	H	L	L	VH	L	VH	M	M	H	M	VH
C22	L	VH	VH	VH	H	VL	M	H	H	H	L	H	VH	VH	M	M	VL	H	H	M
C23	VH	H	H	VH	M	H	VH	VH	H	M	H	H	H	VH	VH	M	M	VH	H	H
C24	M	M	M	VH	VH	VH	VL	M	H	H	H	H	M	VH	VH	VL	M	VH	H	H
C25	H	H	M	M	VH	H	H	VH	VH	VH	H	M	M	M	VH	H	L	VH	VH	VH
C26	VL	M	H	M	H	VL	L	H	VH	H	VL	M	H	M	M	VL	M	H	VH	M
C31	L	L	M	M	M	M	L	M	M	M	M	M	M	M	H	VL	VL	M	M	H
C32	M	VH	H	VH	H	VL	H	H	H	VH	VL	H	H	VH	H	VL	L	M	H	VH
C33	M	VH	M	M	M	M	H	H	H	M	M	M	M	M	M	M	H	H	H	M
C34	VL	VL	H	H	M	H	H	H	H	H	VL	VL	H	H	M	M	VL	H	H	H
C35	M	H	M	H	H	M	H	M	M	H	VL	H	M	M	VL	VL	VL	M	M	VH
C36	VL	H	H	M	VH	VL	H	M	M	H	VL	H	H	M	VH	VL	M	VH	M	H

Table 11 Weighted normalised decision matrix for WSM

SDGs	C11	C12	C13	C14	C15	C16	C21	C22	C23
SDG1	0.029	0.023	0.016	0.016	0.031	0.015	0.038	0.056	0.049
SDG2	0.023	0.030	0.021	0.026	0.033	0.016	0.06	0.043	0.050
SDG3	0.015	0.024	0.024	0.015	0.043	0.013	0.049	0.043	0.049
SDG6	0.025	0.015	0.034	0.011	0.031	0.018	0.039	0.023	0.039
SDG7	0.033	0.024	0.021	0.028	0.041	0.016	0.046	0.049	0.056
SDG12	0.036	0.020	0.031	0.023	0.037	0.014	0.044	0.039	0.056
SDG13	0.036	0.024	0.023	0.025	0.039	0.016	0.048	0.044	0.059
SDG15	0.038	0.024	0.031	0.024	0.044	0.024	0.056	0.036	0.051
SDGs	**C24**	**C25**	**C26**	**C31**	**C32**	**C33**	**C34**	**C35**	**C36**
SDG1	0.044	0.047	0.050	0.051	0.041	0.059	0.013	0.045	0.025
SDG2	0.025	0.039	0.050	0.061	0.037	0.052	0.033	0.045	0.025
SDG3	0.020	0.053	0.050	0.077	0.036	0.040	0.013	0.045	0.025
SDG6	0.034	0.019	0.034	0.060	0.020	0.052	0.011	0.021	0.025
SDG7	0.047	0.044	0.041	0.056	0.035	0.040	0.021	0.043	0.029
SDG12	0.043	0.053	0.043	0.061	0.030	0.044	0.033	0.040	0.026
SDG13	0.053	0.041	0.038	0.072	0.030	0.036	0.021	0.028	0.029
SDG15	0.043	0.047	0.043	0.054	0.024	0.044	0.026	0.030	0.027

Table 12 Weighted normalised decision matrix for WPM

SDGs	C11	C12	C13	C14	C15	C16	C21	C22	C23
SDG1	0.971	0.979	0.962	0.967	0.969	0.976	0.943	0.993	0.972
SDG2	0.956	0.989	0.973	0.987	0.973	0.979	0.980	0.975	0.975
SDG3	0.941	0.982	0.980	0.965	0.988	0.971	0.964	0.975	0.972
SDG6	0.963	0.964	0.994	0.957	0.969	0.982	0.947	0.936	0.955
SDG7	0.978	0.982	0.975	0.989	0.986	0.979	0.961	0.983	0.982
SDG12	0.982	0.974	0.990	0.982	0.980	0.976	0.957	0.968	0.982
SDG13	0.982	0.981	0.977	0.986	0.983	0.980	0.963	0.977	0.986
SDG15	0.986	0.982	0.990	0.984	0.989	0.993	0.975	0.963	0.975
SDGs	**C24**	**C25**	**C26**	**C31**	**C32**	**C33**	**C34**	**C35**	**C36**
SDG1	0.975	0.983	0.980	0.919	0.996	0.995	0.947	0.983	0.984
SDG2	0.939	0.971	0.980	0.940	0.992	0.985	0.988	0.983	0.984
SDG3	0.925	0.991	0.980	0.966	0.990	0.969	0.947	0.983	0.984
SDG6	0.957	0.926	0.952	0.940	0.963	0.985	0.940	0.936	0.984
SDG7	0.979	0.978	0.967	0.930	0.989	0.969	0.969	0.979	0.990
SDG12	0.974	0.991	0.971	0.940	0.983	0.974	0.988	0.975	0.985
SDG13	0.987	0.974	0.961	0.958	0.983	0.960	0.969	0.954	0.990
SDG15	0.974	0.984	0.971	0.930	0.973	0.974	0.978	0.958	0.987

Table 13 Results and rank of FWASPAS method

SDGs	K_i	Rank
SDG1	0.6208	6
SDG2	0.6504	4
SDG3	0.6090	7
SDG6	0.4856	8
SDG7	0.6577	2
SDG12	0.6602	1
SDG13	0.6483	5
SDG15	0.6555	3

FIGURES

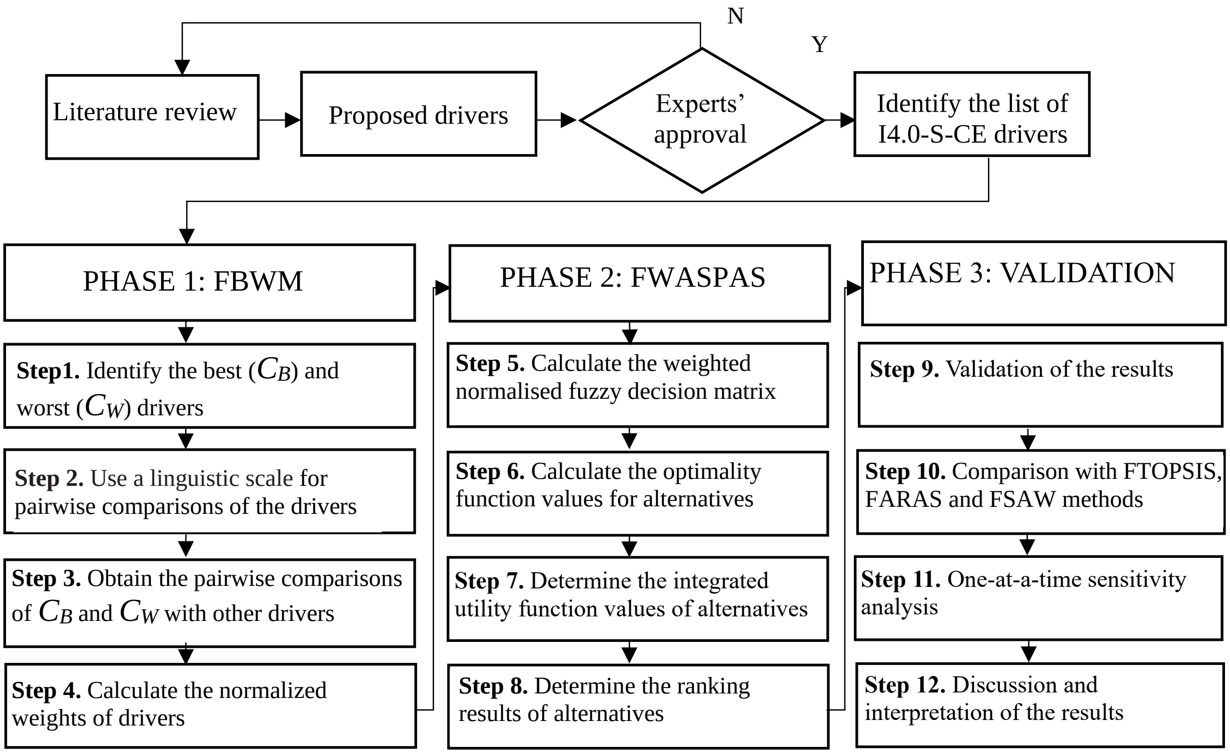

Figure 1 The proposed framework

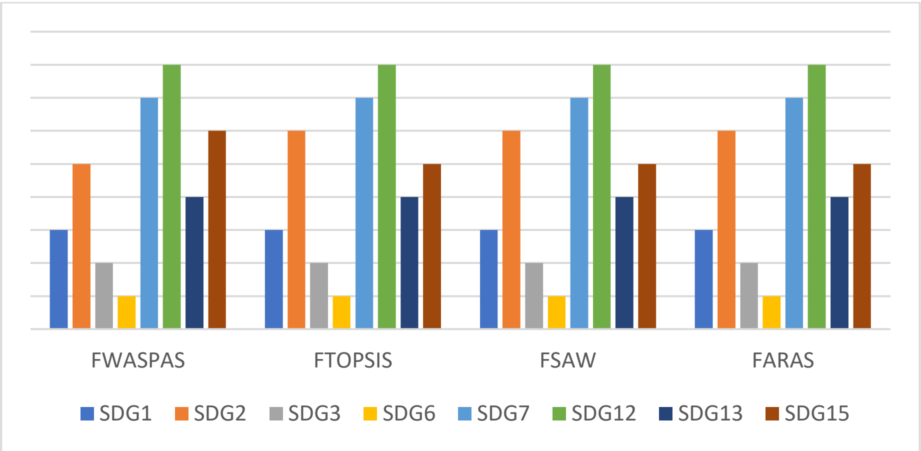

Figure 2 The ranking results of SDGs for different decision-making methods

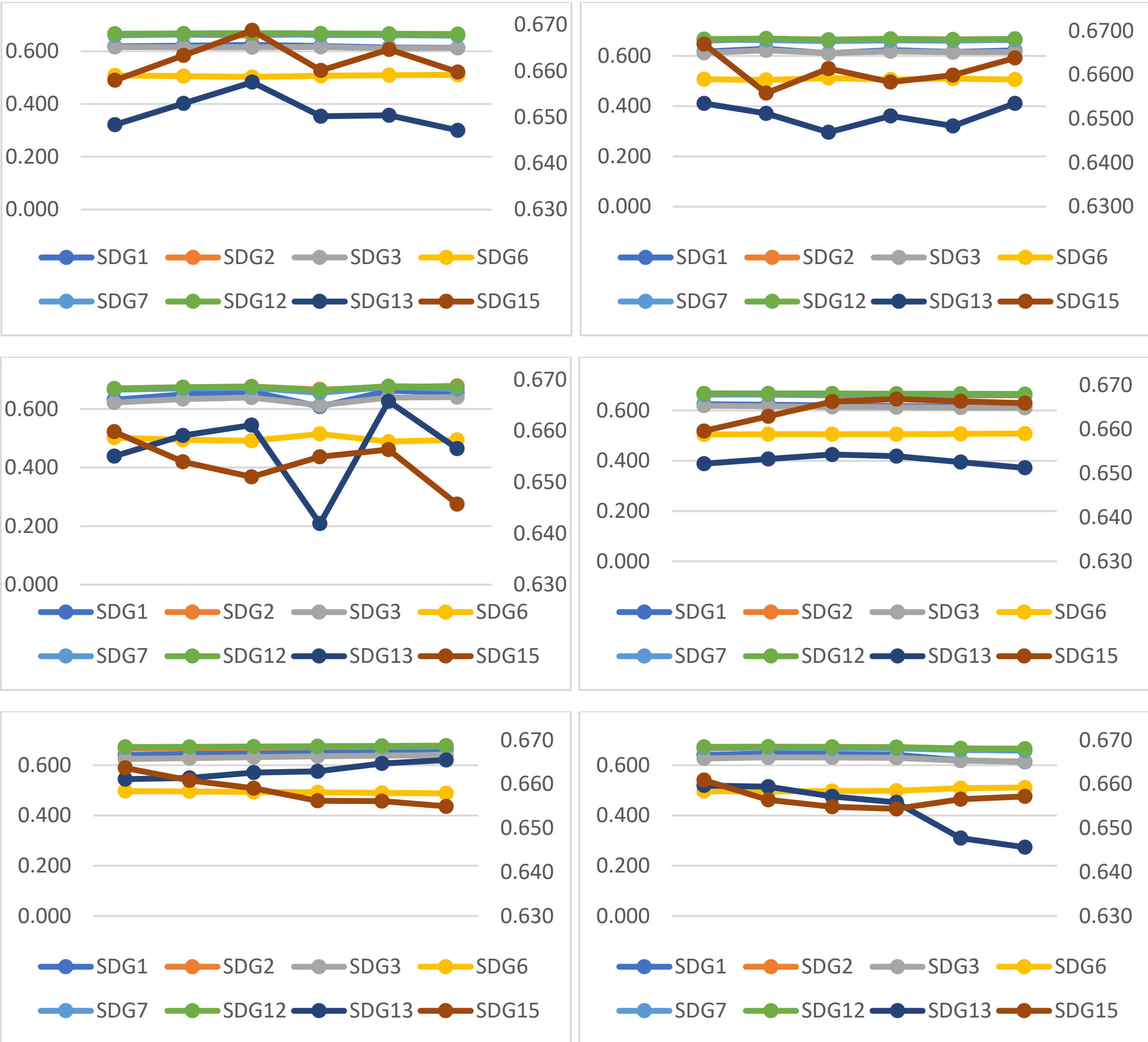

Figure 3 Results of one-at-a-time sensitivity analysis

Appendix

FTOPSIS

Table A1 Positive distance of SDGs alternatives

SDGs	C11	C12	C13	C14	C15	C16	C21	C22	C23
SDG1	0.0098	0.0068	0.0177	0.0117	0.0134	0.0099	0.0222	0.0000	0.0109
SDG2	0.0160	0.0000	0.0130	0.0017	0.0109	0.0083	0.0000	0.0141	0.0098
SDG3	0.0232	0.0051	0.0094	0.0129	0.0014	0.0114	0.0111	0.0141	0.0109
SDG6	0.0134	0.0142	0.0000	0.0165	0.0134	0.0068	0.0211	0.0338	0.0202
SDG7	0.0057	0.0051	0.0123	0.0000	0.0025	0.0083	0.0137	0.0076	0.0032
SDG12	0.0034	0.0096	0.0031	0.0052	0.0067	0.0104	0.0164	0.0184	0.0032
SDG13	0.0034	0.0057	0.0112	0.0024	0.0053	0.0082	0.0125	0.0124	0.0000
SDG15	0.0015	0.0053	0.0031	0.0040	0.0000	0.0000	0.0037	0.0211	0.0085
SDGs	**C24**	**C25**	**C26**	**C31**	**C32**	**C33**	**C34**	**C35**	**C36**
SDG1	0.0093	0.0066	0.0000	0.0267	0.0000	0.0000	0.0207	0.0000	0.0043
SDG2	0.0280	0.0141	0.0000	0.0160	0.0048	0.0093	0.0000	0.0000	0.0043
SDG3	0.0331	0.0000	0.0000	0.0000	0.0064	0.0197	0.0207	0.0000	0.0043
SDG6	0.0191	0.0346	0.0161	0.0185	0.0212	0.0093	0.0226	0.0250	0.0043
SDG7	0.0060	0.0094	0.0087	0.0213	0.0065	0.0197	0.0122	0.0027	0.0000
SDG12	0.0100	0.0000	0.0070	0.0160	0.0109	0.0166	0.0000	0.0055	0.0035
SDG13	0.0000	0.0120	0.0119	0.0053	0.0109	0.0246	0.0122	0.0176	0.0000
SDG15	0.0100	0.0054	0.0070	0.0237	0.0166	0.0166	0.0071	0.0159	0.0020

Table A2 Negative distance of SDGs alternatives

SDGs	C11	C12	C13	C14	C15	C16	C21	C22	C23
SDG1	0.0138	0.0075	0.0000	0.0055	0.0000	0.0015	0.0000	0.0338	0.0095
SDG2	0.0087	0.0142	0.0049	0.0149	0.0025	0.0031	0.0222	0.0211	0.0118
SDG3	0.0000	0.0091	0.0085	0.0041	0.0128	0.0000	0.0111	0.0211	0.0095
SDG6	0.0109	0.0000	0.0177	0.0000	0.0000	0.0046	0.0021	0.0000	0.0000
SDG7	0.0184	0.0091	0.0054	0.0165	0.0109	0.0031	0.0088	0.0264	0.0171
SDG12	0.0209	0.0046	0.0146	0.0114	0.0067	0.0018	0.0071	0.0162	0.0171
SDG13	0.0209	0.0086	0.0067	0.0142	0.0092	0.0033	0.0100	0.0217	0.0202
SDG15	0.0223	0.0090	0.0147	0.0126	0.0134	0.0114	0.0185	0.0135	0.0117
SDGs	**C24**	**C25**	**C26**	**C31**	**C32**	**C33**	**C34**	**C35**	**C36**
SDG1	0.0242	0.0294	0.0161	0.0000	0.0212	0.0246	0.0019	0.0250	0.0000
SDG2	0.0052	0.0214	0.0161	0.0107	0.0170	0.0162	0.0226	0.0250	0.0000
SDG3	0.0000	0.0346	0.0161	0.0267	0.0156	0.0049	0.0019	0.0250	0.0000
SDG6	0.0150	0.0000	0.0000	0.0102	0.0000	0.0162	0.0000	0.0000	0.0000
SDG7	0.0272	0.0257	0.0077	0.0053	0.0150	0.0049	0.0104	0.0223	0.0043
SDG12	0.0231	0.0346	0.0100	0.0107	0.0105	0.0085	0.0226	0.0196	0.0012
SDG13	0.0331	0.0231	0.0046	0.0213	0.0105	0.0000	0.0104	0.0074	0.0043
SDG15	0.0231	0.0293	0.0100	0.0062	0.0047	0.0085	0.0155	0.0092	0.0026

Table A3 Results and rank of FTOPSIS method

SDGs	K_i	**Rank**
SDG1	0.5573	6
SDG2	0.6122	3
SDG3	0.5226	7
SDG6	0.1984	8
SDG7	0.6221	2
SDG12	0.6231	1
SDG13	0.5958	5
SDG15	0.6093	4

FSAW

Table A4 Weighted normalized matrix of SDGs alternatives

SDGs	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C21**	**C22**	**C23**
SDG1	0.0287	0.0144	0.0228	0.0312	0.0228	0.0082	0.0377	0.0462	0.0602
SDG2	0.0225	0.0211	0.0296	0.0380	0.0296	0.0118	0.0599	0.0294	0.0434
SDG3	0.0155	0.0160	0.0245	0.0329	0.0245	0.0154	0.0488	0.0294	0.0434
SDG6	0.0252	0.0093	0.0144	0.0228	0.0155	0.0263	0.0389	0.0154	0.0210
SDG7	0.0331	0.0160	0.0245	0.0329	0.0245	0.0136	0.0463	0.0378	0.0518
SDG12	0.0358	0.0127	0.0194	0.0279	0.0200	0.0227	0.0439	0.0266	0.0378
SDG13	0.0358	0.0160	0.0245	0.0312	0.0239	0.0136	0.0476	0.0322	0.0462
SDG15	0.0375	0.0177	0.0245	0.0312	0.0245	0.0245	0.0562	0.0238	0.0350

SDGs	**C24**	**C25**	**C26**	**C31**	**C32**	**C33**	**C34**	**C35**	**C36**
SDG1	0.0442	0.0339	0.0474	0.0610	0.0474	0.0593	0.0086	0.0105	0.0201
SDG2	0.0253	0.0258	0.0393	0.0529	0.0393	0.0517	0.0239	0.0334	0.0430
SDG3	0.0203	0.0420	0.0556	0.0610	0.0529	0.0403	0.0086	0.0105	0.0201
SDG6	0.0342	0.0122	0.0149	0.0285	0.0185	0.0517	0.0067	0.0086	0.0182
SDG7	0.0471	0.0312	0.0447	0.0556	0.0438	0.0403	0.0143	0.0201	0.0296
SDG12	0.0432	0.0420	0.0556	0.0610	0.0529	0.0441	0.0239	0.0334	0.0430
SDG13	0.0531	0.0285	0.0420	0.0529	0.0411	0.0356	0.0143	0.0201	0.0296
SDG15	0.0432	0.0366	0.0502	0.0556	0.0474	0.0441	0.0182	0.0258	0.0354

Table A5 Results and rank of FSAW method

SDGs	K_i	**Rank**
SDG1	0.6474	6
SDG2	0.6697	3
SDG3	0.6362	7
SDG6	0.5098	8
SDG7	0.6723	2
SDG12	0.6734	1
SDG13	0.6627	5
SDG15	0.6678	4

FARAS

Table A6 Weighted normalized matrix of SDGs alternatives

SDGs	C11	C12	C13	C14	C15	C16	C21	C22	C23
SDG1	0.0375	0.0293	0.0293	0.0207	0.0371	0.0180	0.0478	0.0630	0.0584
SDG2	0.0294	0.0380	0.0380	0.0338	0.0401	0.0199	0.0760	0.0484	0.0597
SDG3	0.0202	0.0315	0.0315	0.0193	0.0520	0.0161	0.0619	0.0484	0.0584
SDG6	0.0329	0.0199	0.0199	0.0149	0.0371	0.0218	0.0494	0.0255	0.0471
SDG7	0.0432	0.0315	0.0315	0.0360	0.0500	0.0199	0.0588	0.0547	0.0672
SDG12	0.0467	0.0257	0.0257	0.0295	0.0451	0.0174	0.0556	0.0432	0.0672
SDG13	0.0467	0.0308	0.0308	0.0331	0.0471	0.0199	0.0603	0.0495	0.0710
SDG15	0.0490	0.0315	0.0315	0.0309	0.0530	0.0300	0.0713	0.0401	0.0609
SDGs	**C24**	**C25**	**C26**	**C31**	**C32**	**C33**	**C34**	**C35**	**C36**
SDG1	0.0532	0.0547	0.0660	0.0681	0.0440	0.0640	0.0168	0.0590	0.0319
SDG2	0.0305	0.0454	0.0660	0.0825	0.0398	0.0558	0.0430	0.0590	0.0319
SDG3	0.0245	0.0610	0.0660	0.1040	0.0384	0.0435	0.0168	0.0590	0.0319
SDG6	0.0413	0.0214	0.0447	0.0801	0.0215	0.0558	0.0143	0.0268	0.0319
SDG7	0.0568	0.0506	0.0546	0.0753	0.0377	0.0435	0.0274	0.0554	0.0370
SDG12	0.0520	0.0610	0.0575	0.0825	0.0327	0.0476	0.0430	0.0518	0.0327
SDG13	0.0640	0.0474	0.0504	0.0968	0.0327	0.0384	0.0274	0.0364	0.0370
SDG15	0.0520	0.0547	0.0575	0.0729	0.0264	0.0476	0.0340	0.0387	0.0344

Table A7 Results and rank of FARAS method

SDGs	K_i	Rank
SDG1	0.9535	6
SDG2	0.9959	3
SDG3	0.9450	7
SDG6	0.7564	8
SDG7	0.9974	2
SDG12	1.0000	1
SDG13	0.9860	5
SDG15	0.9925	4

Table A8 Sensitivity analysis

Case No.	Cases	SDG1	SDG2	SDG3	SDG6	SDG7	SDG12	SDG13	SDG15
1	wc1=0.303; wc2=0.246; wc3=0.451	0.6047	0.6521	0.6038	0.4951	0.6482	0.6552	0.6370	0.6484
2	wc1=0.303; wc2=0.296; wc3=0.401	0.6075	0.6493	0.6030	0.4922	0.6519	0.6565	0.6417	0.6538
3	wc1=0.323; wc2=0.276; wc3=0.401	0.6179	0.6618	0.6135	0.5072	0.6632	0.6671	0.6522	0.6646
4	wc1=0.303; wc2=0.266; wc3=0.431	0.6059	0.6510	0.6035	0.4939	0.6497	0.6557	0.6388	0.6506
5	wc1=0.293; wc2=0.286; wc3=0.421	0.6041	0.6494	0.6018	0.4943	0.6503	0.6556	0.6396	0.6531
6	wc1=0.333; wc2=0.216; wc3=0.451	0.5992	0.6500	0.6003	0.4972	0.6469	0.6539	0.6357	0.6502
7	wc1=0.201; wc2=0.366; wc3=0.433	0.6383	0.6713	0.6279	0.5003	0.6656	0.6713	0.6541	0.6540
8	wc1=0.251; wc2=0.306; wc3=0.443	0.6150	0.6553	0.6098	0.4910	0.6510	0.6577	0.6399	0.6462
9	wc1=0.351; wc2=0.203; wc3=0.446	0.5961	0.6485	0.5981	0.4982	0.6465	0.6532	0.6354	0.6520
10	wc1=0.281; wc2=0.283; wc3=0.436	0.6097	0.6528	0.6061	0.4927	0.6503	0.6566	0.6393	0.6487
11	wc1=0.321; wc2=0.236; wc3=0.443	0.6018	0.6504	0.6016	0.4959	0.6480	0.6546	0.6370	0.6503
12	wc1=0.301; wc2=0.303; wc3=0.396	0.6082	0.6491	0.6031	0.4918	0.6524	0.6568	0.6422	0.6540
13	wc1=0.246; wc2=0.351; wc3=0.403	0.6182	0.6534	0.6097	0.4884	0.6543	0.6590	0.6439	0.6502
14	wc1=0.146; wc2=0.451; wc3=0.403	0.6374	0.6606	0.6216	0.4816	0.6587	0.6636	0.6482	0.6443
15	wc1=0.096; wc2=0.501; wc3=0.403	0.6472	0.6642	0.6277	0.4783	0.6609	0.6659	0.6504	0.6413
16	wc1=0.326; wc2=0.251; wc3=0.423	0.6162	0.6629	0.6135	0.5086	0.6615	0.6665	0.6500	0.6624
17	wc1=0.096; wc2=0.551; wc3=0.353	0.6502	0.6614	0.6269	0.4755	0.6647	0.6674	0.6552	0.6468
18	wc1=0.116; wc2=0.481; wc3=0.403	0.6440	0.6647	0.6267	0.4805	0.6587	0.6648	0.6478	0.6394
19	wc1=0.276; wc2=0.303; wc3=0.421	0.6115	0.6523	0.6065	0.4915	0.6516	0.6572	0.6409	0.6500
20	wc1=0.296; wc2=0.303; wc3=0.401	0.6088	0.6498	0.6038	0.4917	0.6522	0.6569	0.6420	0.6534
21	wc1=0.326; wc2=0.273; wc3=0.401	0.6045	0.6474	0.6006	0.4928	0.6518	0.6559	0.6418	0.6559
22	wc1=0.316; wc2=0.273; wc3=0.411	0.6042	0.6478	0.6009	0.4931	0.6514	0.6558	0.6413	0.6553
23	wc1=0.296; wc2=0.293; wc3=0.411	0.6052	0.6486	0.6018	0.4932	0.6515	0.6561	0.6411	0.6545
24	wc1=0.296; wc2=0.313; wc3=0.391	0.6048	0.6480	0.6012	0.4935	0.6518	0.6561	0.6415	0.6555
25	wc1=0.216; wc2=0.433; wc3=0.351	0.6269	0.6526	0.6124	0.4834	0.6595	0.6619	0.6502	0.6541
26	wc1=0.186; wc2=0.453; wc3=0.361	0.6321	0.6553	0.6162	0.4820	0.6601	0.6630	0.6505	0.6512
27	wc1=0.156; wc2=0.483; wc3=0.361	0.6379	0.6575	0.6198	0.4800	0.6614	0.6643	0.6518	0.6494
28	wc1=0.126; wc2=0.503; wc3=0.371	0.6432	0.6602	0.6236	0.4785	0.6620	0.6654	0.6522	0.6466
29	wc1=0.106; wc2=0.533; wc3=0.361	0.6477	0.6611	0.6258	0.4766	0.6637	0.6667	0.6540	0.6465
30	wc1=0.086; wc2=0.553; wc3=0.361	0.6517	0.6626	0.6283	0.4753	0.6646	0.6676	0.6549	0.6453
31	wc1=0.206; wc2=0.423; wc3=0.371	0.6276	0.6545	0.6139	0.4839	0.6584	0.6618	0.6487	0.6513
32	wc1=0.166; wc2=0.443; wc3=0.391	0.6342	0.6584	0.6190	0.4823	0.6587	0.6630	0.6485	0.6467
33	wc1=0.176; wc2=0.413; wc3=0.411	0.6311	0.6588	0.6182	0.4841	0.6567	0.6620	0.6462	0.6452
34	wc1=0.186; wc2=0.393; wc3=0.421	0.6286	0.6587	0.6171	0.4853	0.6555	0.6613	0.6448	0.6447
35	wc1=0.296; wc2=0.243; wc3=0.461	0.6055	0.6531	0.6048	0.4952	0.6478	0.6552	0.6363	0.6469
36	wc1=0.326; wc2=0.203; wc3=0.471	0.5994	0.6516	0.6015	0.4978	0.6457	0.6536	0.6341	0.6476