DOI: 10.20472/EFC.2024.021.015

HONGJUAN ZHANG
Nanjing University of Aeronautics and Astronautics, China

ASSESSING AGRO-FOOD WASTE VALORIZATION CHALLENGES AND SOLUTIONS CONSIDERING SMART TECHNOLOGIES: AN INTEGRATED FERMATEAN FUZZY MULTI-CRITERIA DECISION-MAKING APPROACH

Abstract:

With the growth of worldwide population and depletion of natural resources, the sustainable development of food system can't be ignored. The demand for agri-food waste valorization practices like high-value compounds production has received widespread attention; however, numerous challenges still exist. The present study aims to identify those challenges of agri-food waste valorization and propose effective solutions based on smart technologies. Based on a systematic literature review, the study combs existing challenges of agri-food waste valorization and constructs a six-dimension conceptual model of agri-food waste valorization challenges. Moreover, the study integrates Fermatean fuzzy set (FFS) with multi-criteria decision-making (MCDM) methods including Stepwise Weight Assessment Ratio Analysis (SWARA), Decision-making Trial and Evaluation Laboratory-Interpretative Structural Modeling Method (DEMATEL-ISM), and Quality Function Deployment (QFD) to evaluate the weights of each dimension, find causal interrelationships among the challenges and fundamental ones, and rank the potential smart solutions. Finally, the results indicate the "Government" dimension is the severest challenge and point out five primary challenges in agri-food waste valorization. Besides, the most potential smart solution is the "Facilitating connectivity and information sharing between supply chain members(S8)", which may help government and related practitioners manage agri-food waste efficiently and also facilitate circular economy.

Keywords:

agri-food waste valorization; smart technology; Fermatean fuzzy set; SWRAR; DEMATEL-ISM; QFD

1 Introduction

In recent years, the global issue of food shortage is severely posing challenges to a significant portion of the population. According to 2024 Global Report on Food Crises issued by Food and Agriculture Organization (FAO), approximately 281 million individuals worldwide are grappling with severe food insecurity that refers to the inability to acquire enough healthy food to meet one's overall nutritional needs [1]. Worse still, over 1.3 billion tonnes of food waste are estimated to be generated each year, which accounts for 13.8% of the total global food production [2]. As part of the food system, agri-food system is responsible for the production of exceedingly high levels of waste [3]. However, the current disposal of agri-food waste, predominantly through landfilling, inflicts considerable damage on the environment such as the emission of greenhouse gases and the contamination of groundwater [4]. Indeed, different from other waste, agri-food waste is rich in complex carbohydrates, bioactive compounds, etc. that hold potential for production of value-added items [5]. To be specific, an abundance of biochemicals are plant-derived, with a lesser amount derived from animals including pomace, peels, leaves, meat by-products and so on [6]. Those bioactive compounds constitute a broad spectrum of molecules with unique structures and properties. They can be utilized in the manufacture of bio-fertilizers, fuel, compost, cosmetics and functional foods [7]. Thus, the valorization of agri-food waste (AFW) has emerged as a possible way for the transformation and sustainable development of the global agri-food system [8]. It is also considered to have a substantial impact on the United Nations' Sustainable Development Goals, specifically Goal No. 2, which aims for zero hunger [9].

In fact, the full utilization of agri-food waste for production of value-added materials remains largely untapped, although its considerable potential has been recognized [10]. On one hand, the valorization of agri-food waste is challenged by its intrinsic complexity, which is marked by heterogeneous composition, short lifespan, and distribution pattern [11]. On the other hand, the operations of agri-food waste valorization encompasses a multifaceted procedure including gathering, transportation, storage, treatment and final disposal [12]. During these processes, a range of challenges, including environmental, social, and economic issues, are likely to emerge [13,14]. Hence, it is imperative to sort out and analyze the barriers that hinder the execution of agri-food waste valorization.

The aforementioned observations highlight the critical need for the adoption of smart technologies to address contemporary obstacles. In recent developments, innovative methods of waste management utilizing smart technologies associated with Industry 4.0 have gained prominence. Pertaining to the agri-food sector, a myriad of smart technologies, particularly Big Data Analytics (BDA), blockchain, Artificial Intelligence (AI), Internet of Things (IoT), digital twins, smart sensors and robotics, and Information and Communication Technology (ICT), could revolutionize traditional practices, enhance efficiency, and promote sustainability [15]. Namely, Artificial Intelligence (AI), which involves programming computers to mimic human behaviors like Machine Learning, Artificial Neural Networks, and Deep Learning, offers immense potential for data-driven science within agri-food supply chains, especially synergized with high-performance computing technologies [16]. Moreover, some business modes comprehensively leverage Big

Data Analytics (BDA) to extract value from agri-food waste, thereby optimizing the existing linear supply chain [17]. Likewise, through the integration of smart technology and e-commerce, a digital platform could address the inefficiencies in agri-food waste management by aggregating and analyzing waste data, and identifying potential business collaborators who may repurpose agri-food waste into commercially valuable products [18]. Nevertheless, the introduction of these technologies in organizations without meticulous plan and scientific analysis is doomed to be unproductive and may even incur substantial financial burdens for the organizations [12]. As a result, it is crucial to contemplate mitigation strategies combining smart technologies, particularly in the context of specific challenges associated with the valorization of agri-food waste.

Therefore, this study seeks to address the subsequent research questions:

Q1: What are the challenges that impede the socialization and standardization of agri-food waste valorization?

Q2: Given the order of priority of challenges and limited resources, which ones should be tackled foremost?

Q3: Considering the mutual influence of these challenges, how can their interrelationships be systematically represented to promote understanding?

Q4: Which smart technological solutions prove to be the most effective in surmounting these challenges taking comprehensive consideration?

Based on those research questions, the goals of this article are as follows:

G1: To identify and rank the challenges linked to the valorization of agri-food waste.

G2: To elucidate the underlying causal and hierarchical interrelationships within these challenges.

G3: To determine the smart technological solutions and confirm the most viable solutions for agri-food waste valorization challenges.

To achieve these goals, this study scrutinizes existing challenges in agri-food waste valorization and formulates a six-dimension conceptual model. Then, the Fermatean Fuzzy Stepwise Weight Assessment Ratio Analysis (FF-SWRAR) is applied to evaluate the significance of each dimension and challenge. Following this, the Fermatean Fuzzy Decision-making Trial and Evaluation Laboratory-Interpretative Structural Modeling Method (FF-DEMATEL-ISM) is employed to discern cause-and-effect dynamics among the identified challenges and core challenges. Finally, the Fermatean Fuzzy Quality Function Deployment (FF-QFD) aids in ranking prospective smart technological solutions.

To the best of authors’ knowledge, prior study has not thoroughly investigated smart technological solutions for agri-food waste valorization. While a study has incorporated smart technology with the valorization of biowaste, it has predominantly focused on a single perspective like AI approach [19]. Additionally, an integrated framework combining FFS and SWRAR, DEMATEL-ISM, and QFD has not been previously employed in valorization of agri-food waste to assess challenges and solutions. So, the study may provide valuable insights for related policymakers to devise strategies aimed at enhancing the valorization of agri-food waste, thereby contributing to the circular economy. Similarly, agri-food waste valorization industry is expected to benefit from the study’s findings, which will guide the formulation of more effective and sustainable decisions.

2 Literature Review

This section discusses the concepts as challenges of agri-food waste valorization, smart technologies in agri-food system, and MCDM methods in waste management. At the end of the section, the research gap is highlighted.

2.1 Challenges of agri-food waste valorization

Currently, the majority of studies concerning the challenges of agri-food waste valorization predominantly concentrate on the exploration of a particular type of agri-food waste or a distinct valorization methodology from the viewpoints of biology and chemistry. For instance, considering the valorization of agri-food waste derived from olive oil and wine production, Tapia-Quirós et al. have advocated for the recovery of phenolic compounds as an effective way and elucidated techniques available for the analysis, extraction, and refinement of polyphenols from the olive mill and winery by-products [20].Also, Mannaa et al. have proposed the integration of insects with organic waste in the bioconversion processes and accentuated the prospective efficacy of these biorefinery systems in surmounting the prevailing challenges associated with agri-food waste [21].

There are few literatures that study the challenges of agri-food waste valorization from a holistic perspective. Berenguer et al. have discussed some pivotal challenges in the valorization of agri-food wastes based on several perspective applications [6], so the scope of challenges identified are limited. And, the study lacks quantitative research and fails to probe into the significance and intrinsic interrelations of these challenges.

2.2 Smart technologies in the agri-food sector

The technological prowess of corporations is crucial in driving their innovative endeavors, which is viewed as one of the most significant dynamic competencies required to maintain enduring competitiveness [22]. In agri-food sector, the application of smart technologies provides the sustainable solutions to different agricultural problems [23]. Therefore, multiple studies have investigated the application status and emerging trends of smart technologies in the agri-food sector [24,25,26]. In terms of different regions, developed countries tend to exhibit a greater engagement with smart technologies [27]. Furthermore, among various smart technologies, the application of blockchain in agri-food supply chain has received more attention [28,29]. Similarly, regarding stakeholders within the agri-food supply chain, downstream companies are more willing to embrace smart technologies to cope with the uncertainty of the supply chain [30].

It is worth noting that although there is literature introducing smart technologies for waste prevention and reduction in the agricultural food industry [31], it remains essential to thoroughly analyze the specific challenges encountered during the valorization of agri-food waste to determine which smart technological solutions can be effectively employed and their priority in addressing these challenges.

2.3 MCDM methods in waste management

Multi-criteria decision-making (MCDM) is a valuable approach for tackling complex decision-making scenarios where multiple criteria need to be taken into account [32]. It provides a structured framework to ensure a more informed and rational choice. In this context, it is evident that MCDM techniques are advantageous, as they enable a systematic comparison of challenges and strategies. What's more, it is common for decision-makers to articulate their subjective judgments through linguistic expressions in reality. This practice poses challenges when attempting to precisely model such information using crisp values. Consequently, to accommodate this imprecision, fuzzy set theory has been widely utilized in various cases [33].

In previous research related to waste management, fuzzy MCDM techniques have been commonly employed to assess challenges and formulate effective strategies. For example, Çelik et al. apply Intuitionistic Fuzzy Multi-Criteria Decision-Making (IFMCDM) methods to identify the most effective hospital for medical waste management in Erzurum, Turkey [34]. Komal integrates Intuitionistic Fuzzy Sets (IFSs) with the Weighted Aggregated Sum Product Assessment (WASPAS) method to assess health-care waste disposal methods [35]. Kabirifar et al. design a hybrid fuzzy MCDM approach to analyze nineteen factors influencing the management of construction and demolition waste [36].

The research methodology of this paper is is improved based on a study conducted by Karuppiah [37]. The researcher combines Fermatean fuzzy set (FFS) with AHP, DEMATEL, and TOPSIS to explore e-waste mitigation strategies. In order to enhance the operability and pertinence of problem analysis, this study introduces another integrated Fermatean fuzzy multi-criteria decision-making approach (i.e. FF-SWRAR, DEMATEL-ISM, and QFD). In contrast to AHP, SWARA necessitates fewer pairwise comparisons for ascertaining weights, thereby rendering it a user-friendly approach for decision-makers [38]. Additionally, QFD is more oriented towards tackling specific issues, while TOPSIS primarily concentrates on the relative gaps between solutions [39].

2.4 Research gap

Based on the above review and analysis, it is evident that while certain studies have explored agri-food waste management from specific perspectives, there remains a dearth of comprehensive examinations regarding the global challenges associated with agri-food waste valorization. Furthermore, the majority of existing research introduces the application of smart technology in the agri-food sector, yet lacks a quantitative analysis. This study endeavors to bridge the gaps by introducing a holistic evaluation framework for agri-food waste valorization challenges and solutions within uncertain environments that not only conduct an exhaustive investigation of diverse factors but also probe into their intricate relationships.

3 Methods

This section is comprised of two subsections: preliminaries and the research framework. In first subsection, the definition of FFS and related operation rules will be introduced in detail. In second subsection, overall research framework including three major stages and integrated four-part methodology(i.e. FFS-SWRAR-DEMATEL-QFD) will be described thoroughly shown as Figure 1.

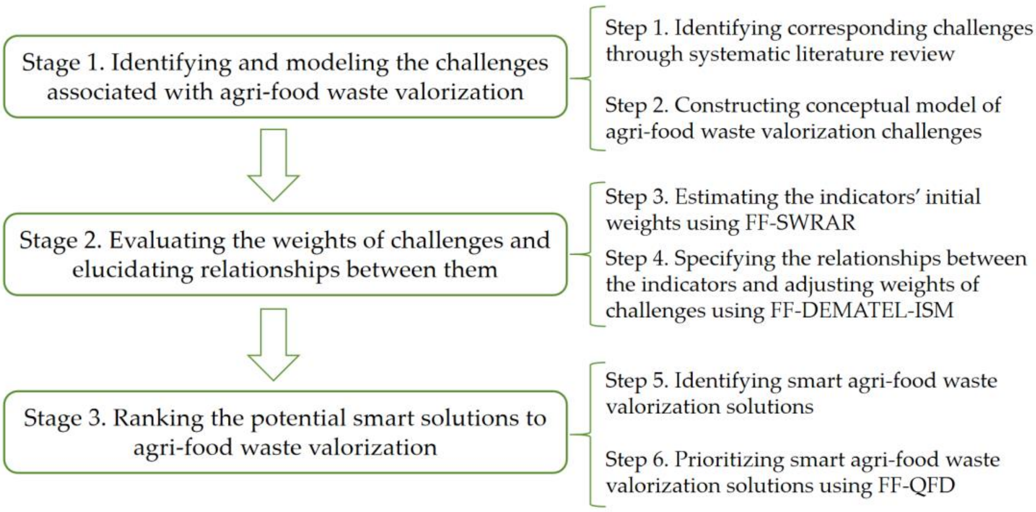

Figure 1. Research framework.

3.1 Preliminaries

3.1.1. Definition of Fermatean fuzzy set

Definition 1. Assuming that X is a universe of discourse, a Fermatean fuzzy set F on X is defined by Senapati and Yager as a function that applied to χ [40]:

$$F = \{\langle \chi, \mu_F(\chi), \nu_F(\chi) \rangle \mid \chi \in \mathrm{X}\} \tag{1}$$

where $\mu_F(\chi) \in [0,1], \nu_F(\chi) \in [0,1]$ denote the degree of membership and non-membership of element $\chi \in [0,1]$ respectively, satisfying $0 \le \mu_F(\chi)^3 + \nu_F(\chi)^3 \le 1$. For any FFS, the degree of indeterminacy of $\chi \in \mathrm{X}$ to F is defined as:

$$\pi_F(\chi) = \sqrt[3]{1 - \mu_F(\chi)^3 - \nu_F(\chi)^3} \tag{2}$$

Besides, $F = (\mu_F, \nu_F)$ is called a Fermatean fuzzy number(FFN).

It's worth noting that FFS, an extension to IFS and PFS, has enlarged the domain of membership and non-membership, which can be shown in Figure 2. So, compared to IFS and PFS, FFS is more efficient in solving multi-criteria decision-making problems under uncertainty.

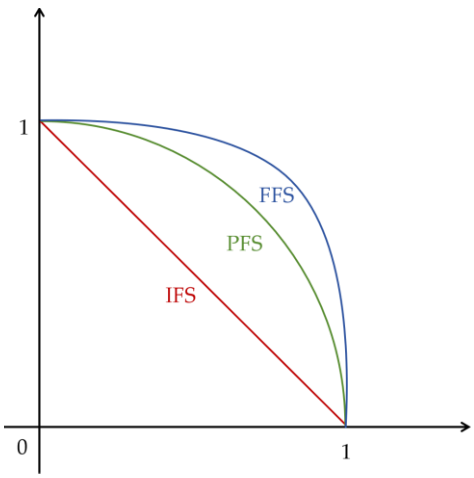

Figure 2. The comparison of IFS, PFS and FFS.

3.1.2. Related operations for Fermatean fuzzy set

Definition 2. Let $F_1 = (\mu_{F1}, \nu_{F1})$ and $F_2 = (\mu_{F2}, \nu_{F2})$ be two FFNs, $\lambda > 0$, defined as [40]:

$$F_1 \oplus F_2 = (\sqrt[3]{\mu_{F1}^3 + \mu_{F2}^3 - \mu_{F1}^3\mu_{F2}^3}, \nu_{F1}\nu_{F2});$$

$$F_1 \otimes F_2 = (\mu_{F1}\mu_{F2}, \sqrt[3]{\nu_{F1}^3 + \nu_{F2}^3 - \nu_{F1}^3\nu_{F2}^3});$$

$$\lambda F_1 = (\sqrt[3]{1-(1-\mu_{F1}^3)^\lambda}, \nu_{F1}^\lambda);$$

$$F_1^\lambda = (\mu_{F1}^\lambda, \sqrt[3]{1-(1-\nu_{F1}^3)^\lambda});$$

Definition 3. Let $F = (\mu_F, \nu_F)$ be a FFN, the score function is defined as [33]:

$$score(F) = \mu_F{}^3 - \nu_F{}^3 \quad (3)$$

For any FFN, $score(F) \in [-1,1]$.

The accuracy function is defined as [33]:

$$accuracy(F) = \mu_F{}^3 + \nu_F{}^3 \quad (4)$$

For any FFN, $accuracy(F) \in [0,1]$.

According to score and accuracy values, the comparison between any two FFNs $F_1 = (\mu_{F1}, \nu_{F1})$ and $F_2 = (\mu_{F2}, \nu_{F2})$ is determined:

If $score(F_1) < score(F_2)$, then $F_1 < F_2$;

If $score(F_1) > score(F_2)$, then $F_1 > F_2$;

If $score(F_1) = score(F_2)$, then

If $accuracy(F_1) < accuracy(F_2)$, then $F_1 < F_2$;

If $accuracy(F_1) > accuracy(F_2)$, then $F_1 > F_2$;

If $accuracy(F_1) = accuracy(F_2)$, then $F_1 = F_2$.

Definition 4. Let $F_i = (\mu_{Fi}, \nu_{Fi})(i = 1, 2, ..., n)$ be a set of FFNs, then a Fermatean fuzzy weighted average(FFWA) is calculated [37]:

$$FFWA(F_1, F_2, ..., F_n) = (\sum_{i=1}^{n} \omega_i \mu_{Fi}, \sum_{i=1}^{n} \omega_i \nu_{Fi}) \tag{5}$$

where $\omega_i \in [0,1]$ is the weight of F_i with $\sum_{i=1}^{n} \omega_i = 1$.

3.2 Research framework

Stage 1. Identifying and modeling the challenges associated with agri-food waste valorization.

Step 1. Identifying corresponding challenges through systematic literature review.

The following framework is adopted to collect articles relevant to agri-food waste valorization [41].

1.Identification: Searching articles considering five aspects in the following order: (1) source type, (2) source quality and relevance, (3) search engine, (4) search period, and (5) search keyword.

2.Screening: Excluding articles returned from the search that don’t completely satisfy search criteria and some duplicate copies.

3.Eligibility: Assessing full text to make sure content relevance.

4.Inclusion: Performing a countercheck and a content analysis on the curated articles.

Step 2. Constructing conceptual model of agri-food waste valorization challenges.

5.Classifying and Modeling: Subsequent to the initial step of investigating and analyzing publications, the challenges of agri-food waste valorization are divided into a six-dimensional conceptual model by experts.

Stage 2. Evaluating the weights of challenges and elucidating relationships between them.

This stage predominantly uses FF-SWRAR to calculate initial weights of indicators. Then, the FF-DEMATEL-ISM method is applied to figure out causal relationship and influence degree among the identified indicators.

Step 3. Estimating the indicators' initial weights using FF-SWRAR

6.Evaluating the expertise level of decision makers [42]: The expertise of each DM is appraised through linguistic expressions delineated in Table 1 along with corresponding FFS equivalents.

Table 1. Linguistic terms of decision makers' expertise level.

Linguistic Terms	Absolute Expertise (AE)	High Expertise (HE)	Moder-ate Ex-pertise (ME)	Less Expertise (LE)	No Expertise (NE)
μ	0.95	0.75	0.55	0.3	0.1
ν	0.1	0.3	0.55	0.75	0.95

Let M represent the count of DMs within the collective. The expertise level of a given DM m, symbolized as $E_m = (\mu_{\mathrm{m}}, \nu_m)$, dictates the influence of the DM's assessment in the decision procedure. The crisp number reflecting a DM's assessment influence among all can be computed:

$$\eta_m = \frac{1+\mu_m^3 - \nu_m^3}{\sum_{m=1}^{M}(1+\mu_m^3 - \nu_m^3)} \tag{6}$$

7.Constructing a linguistic decision matrix for the evaluation of indicators: The linguistic terms infer the linguistic assessment rating of an indicator and further turn into FFN(Table 2) [43]. Consider a FF evaluation matrix $Q = [q_{im}]$ provided by experts, where each element $q_{im} = (\mu_{im}, \nu_{im})$ denotes the corresponding FFN for the linguistic evaluation of DM m for indicator i.

Table 2. Linguistic terms of indicators.

Linguistic Terms	μ	ν
Absolutely Important (AI)/Absolutely High Related (AHR)	0.99	0.10
Very Strong Important (VSI)/Very High Related (VHR)	0.90	0.20
Strong Important (SI) /High Related (HR)	0.80	0.30
Important (I)/Medium High Related (MHR)	0.65	0.40

Equally Important (EI)/Exactly Equal Related (EER)	0.50	0.50
Unimportant (U)/Medium Low Related (MLR)	0.35	0.70
Strong Unimportant (SU)/Low Related (LR)	0.20	0.80
Very Strong Unimportant (VSU)/Very Low Related (VLR)	0.10	0.90
Absolutely Unimportant(AU)/Absolutely Low Related (ALR)	0.01	0.99

8.Combining decision makers' judgments: Let N represent the cardinality of indicator set where $n = 1, 2, ..., N$. Considering expertise weights, the judgments of all DMs on an indicator are aggregated as follows:

$$I_i = (\sum_{m=1}^{M} \eta_m \mu_{im}, \sum_{m=1}^{M} \eta_m \nu_{im}) \quad (7)$$

9.Calculating the comparative significance of each indicator: Firstly, the positive score of each indicator, symbolized as PS_i , is determined as: $PS_i = 1 + score(I_i)$.

Then, rank the indicators in descending order according to the values of PS_i .

Based on the order, the comparative significance CS_i of each indicator is calculated as:

$$CS_i = \begin{cases} 0 & i = 1 \\ PS_i - PS_{i-1} & i > 1 \end{cases} \quad (8)$$

10.Computing the indicator weights [44]: Firstly, the comparative coefficient CC_i is estimated as:

$$CC_i = \begin{cases} 1 & i = 1 \\ CS_i + 1 & i > 1 \end{cases} \quad (9)$$

Then, the recalculated weight q_i of each indicator is determined as:

$$q_i = \begin{cases} 1 & i = 1 \\ \dfrac{q_{i-1}}{CC_i} & i > 1 \end{cases} \quad (10)$$

Finally, the initial weight of each indicator is calculated as:

$$w_i = \frac{q_i}{\sum_{i=1}^{N} q_i} \quad i > 1 \tag{11}$$

Step 4. Specifying the relationships between the indicators and adjusting weights of challenges using FF-DEMATEL-ISM

11.Establishing the FF direct relationship matrix: DMs make pairwise comparisons of indicators to obtain mutual influence strength using Table 3 [45], where influence data among the indicators are expressed by FFN.

Table 3. Linguistic terms of influence score.

Linguistic Terms	Influence Score	FFN
Very High (VH)	4	(0.9,0.1)
High (H)	3	(0.7,0.2)
Low (L)	2	(0.4,0.5)
Very Low (VL)	1	(0.1,0.75)
No influence (NO)	0	(0,1)

12.Constructing aggregate FF direct relationship matrix: Use FFWA operator to aggregate the judgments of multiple DMs as follows:

$$A = \begin{bmatrix} (\mu_{F11}, \nu_{F11}) & (\mu_{F12}, \nu_{F12}) & \cdots & (\mu_{F1n}, \nu_{F1n}) \\ (\mu_{F21}, \nu_{F21}) & (\mu_{F22}, \nu_{F22}) & \cdots & (\mu_{F2n}, \nu_{F2n}) \\ & & \cdots & \\ (\mu_{Fn1}, \nu_{Fn1}) & (\mu_{Fn2}, \nu_{Fn2}) & \cdots & (\mu_{Fnn}, \nu_{Fnn}) \end{bmatrix} \tag{12}$$

13.Defuzzification [46]: The FF defuzzification function φ is employed to turn the FFN matrix A into crisp number matrix X as follows:

$$\varphi_{ij} = 1 + score(\mu_{Fij}, \nu_{Fij}) \tag{13}$$

$$X = \begin{bmatrix} \varphi_{11} & \varphi_{12} & \cdots & \varphi_{1n} \\ \varphi_{21} & \varphi_{22} & \cdots & \varphi_{2n} \\ & & \cdots & \\ \varphi_{n1} & \varphi_{n2} & \cdots & \varphi_{nn} \end{bmatrix} \tag{14}$$

14.Normalization: The new aggregate direct relationship matrix X is normalized using following equations:

$$G = s^{-1} X \tag{15}$$

where $s = \max(\max_{1 \le i \le n} \sum_{j=1}^{n} x_{ij}, \max_{1 \le j \le n} \sum_{i=1}^{n} x_{ij})$.

15.Constructing total relationship matrix T :

$$G = s^{-1} X \tag{16}$$

where I is the identity matrix.

16.Classifying indicators into cause and effect groups as follows:

$$D = \left(\sum_{j=1}^{n} t_{ij} \right)_{1 \times n} = (t_i)_{1 \times n} \tag{17}$$

$$C = \left(\sum_{i=1}^{n} t_{ij} \right)_{n \times 1} = (t_i)_{n \times 1} \tag{18}$$

The value of $C + D$ represents centrality, while the value of $C - D$ represents causality.

17.Adjusting the weights of challenges: Combine centrality and initial weights calculated by SWRAR to obtain final weights of challenge using weighted average method. The specific weights are determined by relevant experts.

18.Obtaining initial reachability matrix(IRM): According to the following formula, total relationship matrix T is converted to the initial reachability matrix R . The threshold λ can be set based on the sum of mean and standard deviation in statistical distribution, effectively reducing subjective influence [47].

$$R = \begin{cases} 1 & t_{ij} \ge \lambda \\ 0 & t_{ij} \le \lambda \end{cases} \tag{19}$$

19.Constructing final reachability matrix(FRM): To obtain the FRM, the transitivity of the IRM is examined. According to the transitivity rule, if factor i has an impact on factor j , and if factor j affects factor k , then factor i also impacts factor k [48].

20.Partitioning level: A level partitioning operation was performed to acquire the reachability, antecedent, and intersection set.

Stage 3. Ranking the potential smart solutions to agri-food waste valorization.

In the stage, some solutions considering smart technologies are proposed to promote valorization of agri-food waste. Then, the FF-QFD method is utilized to prioritize them.

Step 5. Identifying smart agri-food waste valorization solutions

21.Identifying strategies in the perspective of smart technologies: Based on relevant literature and experts' suggestions in the field, some potential strategies are provided.

Step 6. Prioritizing smart agri-food waste valorization solutions using FF-QFD

The steps of FF-QFD are explained as follows:

22.Specifying the indicators: The indicators(i.e. challenges and solutions) have been decided in step 1 and 4.

23.Obtaining the importance weights of challenges: Each challenge has been evaluated based on FF-SWRAR.

24.Defining relationships between challenges and solutions: DMs use the scale as in Table 2 to define the relationship matrix $R_{ij}\left(i=1,2,....,n,\ j=1,2,...,k\right)$. If there is no relationship between the challenge and solution, the cell is left blank.

25.Calculating the relative importance of solutions: The relative importance $RI_j\left(j=1,2,...,k\right)$ of solution j is determined using FFWA operator as:

$$RI_j=\sum_{i=1}^{n}w_iR_{ij}=(\sum_{i=1}^{n}w_i\mu_{Fi},\sum_{i=1}^{n}w_i\nu_{Fi})\left(j=1,2,...,k\right) \quad (20)$$

26.Creating correlation matrix: The correlations $S_{jj'}\left(j\neq j'\right)$ between solutions are created using the scale as in Table 2. There are three states that described an interrelationship: positive(+), negative (-), or non-existent (designated by a blank box).

27.Calculating score value for positive and negative correlations: Aggregate DMs' judgments of correlation matrix by FFWA operator and calculate final score value.

28.Finding absolute importance for each solution [49]: The absolute importance $AI_j\left(j=1,2,...,k\right)$ for solution j can be computed as:

$$AI_j=RI_j\oplus\sum_{j'=1}^{k}S_{jj'}\otimes RI_{j'}(j=1,2,...,k;\ \ j'\neq j) \quad (21)$$

29.Obtaining final score value of solutions and ranking them: Use FF defuzzification function to obtain crisp value of each solution and prioritize these solutions.

4 Results and Discussion

In the preceding section, the general outline of a complete study has been established. Detailed calculations and corresponding results of the FF-MCDM studies are described in the following subsections.

4.1 Results

According to the three main stages of research framework, the applied procedure based on FF-SWRAR, FF-DEMATEL-ISM, FF-QFD is summarized as follows:

Stage 1. Identifying and modeling the challenges associated with agri-food waste valorization.

Step 1. Identifying corresponding challenges through systematic literature review.

The Web of Science databases were utilized to search for theses topics "agri-food waste management," "agri-food waste management," "agri-food waste valorization," and "agri-food waste valorization." This search yielded 573 publications spanning from 2019 to April 2024. Following a series of screening procedures, a refined compilation of 43 articles was selected for further analysis.Then, the challenges of agri-food waste valorization were identified.

Step 2. Constructing conceptual model of agri-food waste valorization challenges.

Based on the literature [50], experts categorized the challenges into six distinct dimensions: Organization, Environment, Technology, Economy, Government, and Society. (Table 4).

Table 4. Conceptual model of agri-food waste valorization challenges.

Dimensions	Codes	Factors	Codes	References
Organization	C1	Poor logistical and infrastructural systems	C11	[73,74,79,82]
		Less standardized operational practices	C12	
		The absence of intermediary companies/departments collecting and directing wastes to specific points for processing	C13	
		Rare cooperation between supply chain members in the process of agri-food waste valorization	C14	
		Lack of instructions about approaches of agricultural waste valorization	C15	
		No safety assessment of biotechnologically materials	C16	
Environment (including biochemical property)	C2	The region-dependent and seasonal availability of a waste stream	C21	[77,86,87,88]
		Variable quality of the waste stream due to deterioration	C22	
		New product safety issues like contamination of heavy metals	C23	
		High sensitivity of microorganisms to operating conditions	C24	
		High standard on properties of the raw materials like element proportion, moisture content	C25	
		Production of environmental footprint in extraction processes	C26	
Technology	C3	Lack of the most efficient and cost-effective extraction method for specific waste streams	C31	[76,82,84,85,78]
		Limited technological capabilities available for sorting, safe storing, and distribution of food waste	C32	

		No full understanding of emerging technologies	C33	
		Loss of biocompounds caused by conventional extraction technology	C34	
		High energy consumption of technology	C35	
Economy	C4	High transport costs due to collection and processing of biomasses	C41	[71,73,75,82,83]
		High expenses related to the techniques utilized	C42	
		The shortage of investment in technologies/solutions	C43	
Government	C5	Lack of robust and detailed legal and regulatory foundation	C51	[72,80,82,89]
		The absence of agri-waste management digital platforms	C52	
		Lack of relevant incentive systems	C53	
Society	C6	Less trust of consumers in safety of new products based on agricultural by-products	C61	[73,80,81]
		Little public awareness about agri-food waste valorization	C62	
		Obscure consumer acceptance due to changes in sensory quality	C63	

Stage 2. Evaluating the weights of challenges and elucidating relationships between them.

Step 3. Estimating the indicators' initial weights using FF-SWRAR

In this step, the FF-SWRAR methodology was employed to determine initial weights of each challenge through assessment of three experts. Table 5 outlines the respective expertise levels of these three experts.

Table 5. Expertise levels of decision makers.

DM	Degree of Expertise	Influence of assessment
E_1	HE	0.411
E_2	ME	0.295
E_3	ME	0.295

Furthermore, Table 6 provides a comprehensive overview of the local weights and overall weights assigned to each challenge.

Table 6. Weights of dimensions and challenges.

Dimensions	Factors	Local weights of challenges	Overall weights of challenges
C1 0.246	C11	0.23	0.05

	C12	0.21	0.02
	C13	0.20	0.06
	C14	0.16	0.05
	C15	0.11	0.04
	C16	0.09	0.03
	C21	0.24	0.02
	C22	0.20	0.02
C2 0.123	C23	0.18	0.02
	C24	0.16	0.01
	C25	0.14	0.03
	C26	0.09	0.02
	C31	0.31	0.05
	C32	0.26	0.06
C3 0.186	C33	0.20	0.02
	C34	0.13	0.02
	C35	0.10	0.04
	C41	0.39	0.03
C4 0.102	C42	0.35	0.04
	C43	0.26	0.04
	C51	0.33	0.08
C5 0.252	C52	0.36	0.09
	C53	0.31	0.08
	C61	0.44	0.04
C6 0.091	C62	0.31	0.03
	C63	0.25	0.02

Clearly, "Government (C5)" and "Organization (C1)" emerge as the most critical dimensions. Moreover, the most pivotal challenges are “The absence of agri-waste management digital platforms(C52)”, “Lack of relevant incentive systems(C53)”, “Lack of robust and detailed legal and regulatory foundation(C51)”, “Limited technological capabilities available for sorting, safe storing, and distribution of food waste(C32)”, “The absence of intermediary companies/departments collecting and directing wastes to specific points for processing(C13)”.

Step 4. Specifying the relationships between the indicators and adjusting weights using FF-DEMATEL-ISM

In this step, the FF-DEMATEL-ISM was used to clarify interrelationships among challenges. Table 7 presents the identified causal relationships.

Table 7. Causal relationships of challenges.

Factors	C	D	C+D	Rank	D-C	Category
C11	1.28	0.01	1.286	2	-1.267	effect
C12	0.60	0.09	0.692	8	-0.514	effect
C13	0.77	0.11	0.885	6	-0.657	effect
C14	0.32	0.36	0.676	10	0.036	cause
C15	0.20	0.36	0.556	13	0.157	cause
C16	0.22	0.23	0.457	19	0.008	cause
C21	0.00	0.24	0.239	25	0.239	cause
C22	0.38	0.11	0.491	16	-0.264	effect
C23	0.41	0.12	0.532	15	-0.291	effect
C24	0.00	0.28	0.281	24	0.281	cause
C25	0.09	0.00	0.093	26	-0.093	effect
C26	0.35	0.00	0.346	23	-0.346	effect
C31	0.39	0.74	1.138	3	0.351	cause
C32	0.29	0.47	0.752	7	0.180	cause
C33	0.29	0.39	0.688	9	0.100	cause
C34	0.42	0.00	0.420	20	-0.420	effect
C35	0.17	0.18	0.354	22	0.008	cause
C41	0.37	0.23	0.593	12	-0.141	effect
C42	0.39	0.16	0.551	14	-0.237	effect
C43	0.44	0.66	1.098	5	0.226	cause
C51	0.17	0.31	0.477	17	0.140	cause
C52	0.07	1.04	1.113	4	0.971	cause
C53	0.18	1.34	1.524	1	1.160	cause
C61	0.41	0.06	0.471	18	-0.343	effect
C62	0.00	0.60	0.599	11	0.599	cause
C63	0.00	0.40	0.404	21	0.404	cause

And Table 8 illustrates the derived hierarchical structure.

Table 8. Hierarchical structure of challenges.

Level	Factors
1	C25
2	C11,C61
3	C13,C23,C26,C34
4	C12,C22,C35,C41,C42
5	C14,C16,C31,C32
6	C15,C33,C43,C51
7	C62,C63
8	C21,C24,C52,C53

Given the values of C−D in Table 7, the challenges have been categorized into cause-and-effect groups as depicted in Figure 3. In the cause group, the most important challenges are “Lack of relevant incentive systems(C53)” and “The absence of agri-waste management digital platforms(C52)”. In the effect group, the most important challenges are “The absence of intermediary companies/departments collecting and directing wastes to specific points for processing(C13)” and “Poor logistical and infrastructural systems(C11)”. Based on C+D values, the prominence of the critical factors have been evaluated. The top five ranked challenges are “Lack of relevant incentive systems(C53)”, “Poor logistical and infrastructural systems(C11)”, “Lack of the most efficient and cost-effective extraction method for specific waste streams(C31)”, “Lack of robust and detailed legal and regulatory foundation(C51)”, “The shortage of investment in technologies/solutions(C43)”.

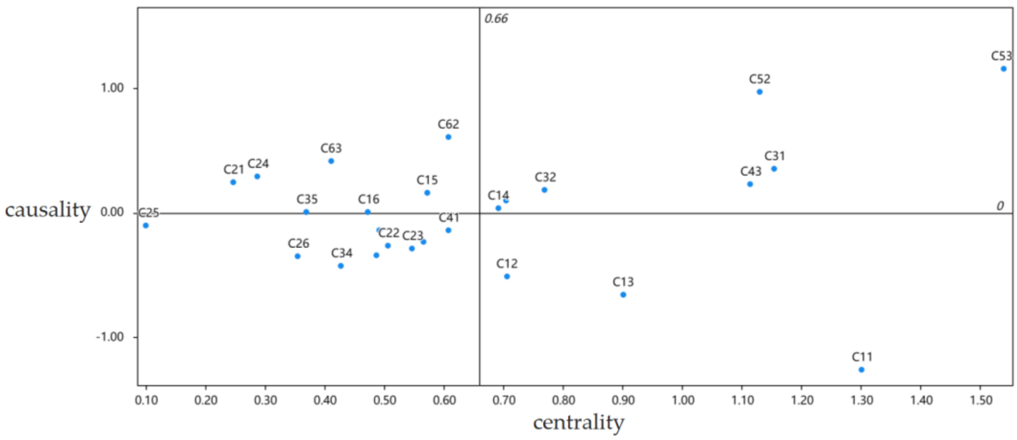

Figure 3. Centrality and causality of challenges.

After adjusting weights, the final most important challenges are “Lack of relevant incentive systems(C53)”, followed by “The absence of agri-waste management digital platforms(C52)”, “Poor logistical and infrastructural systems(C11)”, “Lack of the most efficient and cost-effective extraction method for specific waste streams(C31)”, “The absence of intermediary companies/departments collecting and directing wastes to specific points for processing(C13)”.

According to the analysis results of ISM(Table 8), the challenges of agri-food waste valorization can be divided into eight levels. The essential causal factors at the bottom level are “The region-dependent and seasonal availability of a waste stream(C21)”, “High sensitivity of microorganisms to operating conditions(C24)”, “Lack of relevant incentive systems(C53)” and “The absence of agri-waste management digital platforms(C52)”.

Stage 3. Ranking the potential smart solutions to agri-food waste valorization.

Step 5. Identifying smart agri-food waste valorization solutions

An in-depth investigation was conducted in the Web of Science databases, encompassing all existing publications about the utilization of smart technologies in agri-food waste valorization. Additionally, insights from professional experts were solicited. Consequently, a total of 18 innovative smart solutions were identified(Table 9).

Table 9. Smart solutions to agri-food waste valorization.

Codes	Solutions	References
S1	Employing AI to predict and classify the properties or characteristics of biowaste	[17,25,66,90-112]
S2	Utilizing AI to predict the volatile organic compounds (VOCs) and supply for waste materials	
S3	Improving transparency and safety of agri-food supply chains through contamination tracing and efficient food production system e.g., IoT, Blockchain, Big Data, RFID tags, GIS	
S4	Obtaining real-time and up-to-date digital information on crop growth, safety, and nutrition by UAVs, Cloud-computing, GIS	
S5	Using digital devices and platforms in rural agriculture as early warning system by information and ICT, RFID tags, remote sensors	
S6	Cooperating between technology providers and adopters to advance sustainable agri-food supply chain management using remote sensors, weather forecasting systems, bio-stimulants	
S7	Integrating innovative agricultural technologies with farmers' traditional knowledge and constructing a knowledge-sharing platform	
S8	Facilitating connectivity and information sharing between supply chain members	

S9	Designing agri-food waste apps to link manufacturers, supermarkets, restaurants, and individual households	
S10	Searching and analyzing current databases to guide the selection of suitable agri-food waste valorization approach through AI	
S11	Identifying the exact parameters in the operational process based on BDA together with the sensors	
S12	Automatically identifying consumer needs to inform manufacturers and retailers utilizing text mining and information sharing platform	
S13	Applying IoT to monitor environmental parameters like temperature, dissolved oxygen and ph in the production process	
S14	Using intelligent algorithms for site selection and transportation path planning	
S15	Minimizing the carbon footprint of the entire supply chain by Cloud-computing	
S16	Implementing autonomous robots to reduce costs and improve operational professionalism	
S17	Increasing awareness of cybersecurity at all stages of the supply chain	
S18	Adopting digital twins to evaluate agricultural food waste quality and tailor supply chains to reduce losses	

Step 6. Prioritizing smart agri-food waste valorization solutions using FF-QFD

As depicted in Table 10, the results of FF-QFD analysis reveal that, in addressing current challenges, the most highly prioritized solutions are “Facilitating connectivity and information sharing between supply chain members(S8)”, “Improving transparency and safety of agri-food supply chains through contamination tracing and efficient food production system e.g., IoT, Blockchain, Big Data, RFID tags, GIS(S3)”, “Utilizing artificial intelligence (AI) to predict the volatile organic compounds (VOCs) and supply for waste materials(S2)”.

Table 10. Importance of smart solutions.

Codes	Absolute importance	Rank
S1	0.016	10
S2	0.142	3

S3	0.154	2
S4	0.069	5
S5	0.042	6
S6	0.008	12
S7	0.020	9
S8	0.365	1
S9	0.099	4
S10	0.014	11
S11	0.002	17
S12	0.021	8
S13	0.003	14
S14	0.003	15
S15	0.004	13
S16	0.002	16
S17	0.002	18
S18	0.034	7

4.2 Discussion

This section focuses on the in-depth analysis of the aforementioned results. In terms of different dimensions of challenges, “Government(C5)” ranks the highest. Typically, the local government assumes a guiding role in a project, with its primary responsibility being to facilitate the participation of enterprises and the public. Particularly in the case of agri-food waste value-added initiatives, which necessitate substantial initial investments and yield returns over an extended duration, the role of governmental guidance and backing is imperative. In an empirical study, Xiang & Gao proves that government support exerts a remarkably positive influence on the sustainable development of agricultural sector [51]. Notably, agricultural extension services and ecological subsidies, as key constituents of government support, contribute significantly to agricultural sustainability. What’s more, through evolutionary games, some scholars demonstrate that it is crucial to enhance government's accountability and regulatory proficiency, robustly pursue technological advancements and refine the incentive and disciplinary mechanisms to achieve both specialization and socialization of agricultural waste valorization [52]. The second important dimension is “Organization(C1)”. Related business organizations constitute a significant driving force in the generation of waste, as well as the innovation and utilization of Industry 4.0 technologies [53]. So, organizations serve as the actual main participants responsible for the valorization of agri-food waste. Should there be a lack of active engagement, an absence of instructions on agri-food waste valorization methods, and infrequent collaboration with other supply chain members, they are prone to adopting unscientific and unsystematic practices in managing agri-food waste, overlooking potential flaws in the logistical and infrastructural systems. Take Kampala city for example, to achieve environmental, economic and technical goals within urban settings, related organizations should carefully choose suitable technology-driven systems for agri-food waste valorization [54].

According to the Pareto principle [55], also known as the “80/20” rule, a deeper analysis has been conducted on the top five challenges out of a total of 26 identified challenges. The foremost challenge lies in “Lack of relevant incentive systems(C53)”, which falls under the "cause" category. Actually, in Pakistan, Malaysia, and China, research finds that government incentives have a positive effect on the innovation of circular economy in small and medium enterprises [56]. Moreover, in Australia, lack of government incentive is a major barrier to develop circular economy [57]. However, only a few countries, such as France, Italy, Austria, and Germany, have provided financial support in certain areas of agri-food waste valorization, but such financial support is only applicable to small-scale pilot projects and cannot be scaled up for large-scale promotion [58].

The following challenge is “The absence of agri-waste management digital platforms(C52)” belonging to the "cause" category. With regard to the governmental role, the traditional emphasis has predominantly centered on resources of financial wealth and administrative authority. However, other potential roles that governments could assume in fostering the development of agri-food waste valorization are often overlooked [59]. Specifically, the possibility for a government to leverage its central position within pivotal networks to gather advanced resources, thus creating a comprehensive digital platform to coordinate stakeholders and establish partnerships. Indeed, a key characteristic of the advancement of agri-food waste valorization lies in harnessing intricate networks of diverse actors, each possessing a range of requisite skills. Besides, the factor also highlights the necessity of using smart technology to address existing challenges.

The third important challenge is “Poor logistical and infrastructural systems(C11)”, within the "effect" category. The factor is significantly influenced by numerous other variables, especially “The absence of relevant incentive systems(C53)”, “The absence of agri-waste management digital platforms(C52)”, and “ The lack of the most efficient and cost-effective extraction method for specific waste streams(C31)”. These contributory factors largely constrain the effectiveness of logistical and infrastructural systems in managing agricultural waste. Due to the factors C53 and C31, numerous agricultural enterprises bear elevated risks when confronted with substantial investments in technology, thereby deterring them from proactive upgrading of their current infrastructural facilities [60]. In addition, the valorization of agri-food waste is not feasible solely through the efforts of a single enterprise, but requires the collaboration across the entire industry chain and even societal engagement. Hence, the absence of a unified digital management platform(C52) poses a significant obstacle in achieving seamless and standardized logistics systems.

Next, the challenge is “The lack of the most efficient and cost-effective extraction method for specific waste streams(C31)” under the "cause" category. Extracting effective substances from agricultural food waste is a decisive step in valorization of agricultural food waste. Taking the extraction of cellulose as an example, isolating cellulose from biomass poses a significant challenge due to the recalcitrant nature of biomass, which inherently limits the accessibility of cellulose for value-adding applications [61]. Furthermore, the diverse range of agri-food sources containing cellulose renders it exceedingly difficult to devise a standardized extraction method capable of efficiently recovering cellulose across all types of sources. It is recommended that the forthcoming five years should be dedicated to exploring the innovative thermal extraction technologies, with a comprehensive techno-economic analysis conducted to thoroughly assess the feasibility and effectiveness of implementing these technologies in the extraction process of agricultural byproducts [62].

The fifth significant challenge, classified under the "effect" category, pertains to “The absence of intermediary companies/departments collecting and directing wastes to specific points for processing(C13)”. In fact, as the waste bank is incapable of recycling the waste independently, the supply chain relies on a recycling factory to accomplish this task [63]. Besides the government dimension, the two most important influencing factors to the challenge are “Limited technological capabilities available for sorting, safe storing, and distribution of food waste(C32)” and “Rare cooperation between supply chain members in the process of agri-food waste valorization(C14)”. The former underscores the substantial resource allocation to streamline the procurement of agri-food waste, thereby guaranteeing consistency, microbial safety, and superior quality for processing of waste, which once again demonstrates the necessity of government and social support [64]. The latter reason is aligned with a finding that the conversion of food waste into valuable products necessitates a concerted effort spanning the entire value chain and adopting a comprehensive food system viewpoint, which entails a profound understanding of the boundaries stemming from the subject's dynamic characteristics and interconnected dependencies [65].

The factors at the bottom level are fundamental factors. C21 and C24 are inherent attributes of the research subject. Specifically, the spatiotemporal distribution of agri-food waste and its high sensitivity to environment fundamentally impacts the cost and quality of biomass value-added processes. C53 and C52, in “Government” dimension, play an external driving role in the valorization of agri-food waste, fully leveraging the aforementioned governmental prowess in resources and organization.

The subsequent discussion delves deeper into the top three solutions pertaining to smart technologies. Among these, the solution that emerges as the most effective is "Facilitating connectivity and information sharing between supply chain members by digital tools(S8)”. Enhanced visibility and transparency within the supply chain empower members to identify and mitigate risks in a more efficient manner, thereby reducing the likelihood of disruption, particularly considering region-dependent and seasonal availability of the waste stream. Additionally, through swift exchange of information, supply chain members respond promptly to changes in market conditions in regard to obscure consumer preference. The solution also contributes to the establishment of a comprehensive agri-food waste management platform on a large scale. Among the digital tools, big-data management appears to be the most suitable for achieving S8, given its capability to facilitate the collection and sharing of diverse data types among organizations, ultimately enhancing the accuracy of outcomes [66]. The second important solution is “Improving transparency and safety of agri-food supply chains to customers through contamination tracing and efficient food production system e.g., IoT, Blockchain, RFID tags(S3)". Merely enhancing information exchange among enterprises within the supply chain is insufficient. It is essential to address the safety concerns of customers pertaining to new agri-food value-added products. Consequently, it becomes necessary to synchronize information derived from diverse production processes with customers to ensure their trust and satisfaction. In fact, the successful valorization of agri-food by-products heavily relies on robust traceability and rigorous quality monitoring in production and logistic system [29]. The third important solution lies in "Utilizing artificial intelligence (AI) to predict the volatile organic compounds (VOCs)(S2)". In practice, the variability of feedstock derived from biowaste extremely hinders the widespread utilization of value-added products. To overcome the difficulties, the valorization of agri-food waste has embraced artificial intelligence (AI), a novel approach, as a potential solution. According to diverse components of biomass, the overall dataset for training and testing in AI learning and the application of AI algorithms is diverse [19].

5 Conclusion

This study advances the existing literature by proposing solutions to the challenges of agri-food waste valorization considering smart technologies in the context of Industry 4.0. Through a comprehensive literature review and insights from agricultural experts, a wide range of challenges have been identified and subsequently categorized into six distinct dimensions: Organization, Environment, Technology, Economy, Government, and Society. Then, a novel integrated MCDM approach including FFS, SWRAR-DEMATEL-ISM-QFD is employed to evaluate the challenges and potential solutions in the light of expert insights. Prior to this study, the comprehensive framework of FF-SWRAR-DEMATEL-ISM-QFD had not been implemented. Based on the findings of the FF-SWRAR, the "Government" dimension emerges as the most crucial, with a significant weight of 0.252, indicating its importance in addressing the challenges of agri-food waste valorization. Therefore, the government bears a paramount obligation to proactively foster the socialization of agri-food waste valorization, striving towards high-quality and environmentally sustainable agricultural development paradigms. Furthermore, it's responsible to steer resource allocation in an efficient manner and catalyze the transformation and upgrading of the food system to enhance its overall sustainability and efficiency. According to the final weights of challenges, the top five most pivotal challenges are: "The absence of relevant incentive systems(C53)", "The absence of agri-waste management digital platforms(C52)", "Poor logistical and infrastructural systems(C11)", "The lack of the most efficient and cost-effective extraction method for specific waste streams(C31)" and "The absence of intermediary companies/departments collecting and directing wastes to specific points for processing(C13)". Next, the FF-DEMATEL-ISM method divides these challenges into cause and effect groups, and identify the fundamental factors. Specifically, 14 factors are categorized as the cause group, 12 factors are categorized as the effect group, and all these factors are further segmented into 8 levels. Finally, FF-QFD prioritizes smart technology solutions in accordance with the varying weight of current challenges. Among these, three solutions stand out as the most significant: "Facilitating connectivity and information sharing between supply chain members by digital tools(S8)", "Improving transparency and safety of agri-food supply chains to customers through contamination tracing and efficient food production system e.g., IoT, Blockchain, RFID tags(S3)" and "Utilizing artificial intelligence (AI) to predict the volatile organic compounds (VOCs)(S2)".

5.1 Theoretical Implications

By reviewing and categorizing the existing challenges of agri-food waste valorization into several macro-dimensions that should be considered as social issues, this study provides corresponding perspectives for researchers from different sectors of society who engage in agri-food waste management, enabling them to have a more comprehensive understanding of this issue. Additionally, against the backdrop of sustainable development and digitization, this study is an initial attempt to propose solutions to existing challenges based on smart technology, inspiring managers in the agricultural sector to devise more scientific methods while promoting technological advancements in the agricultural sector. Moreover, this study introduces a new MCDM methodological framework, as evaluation methods in the FFS environment are rarely applied in the agri-food waste sector. This methodological system can be transferred to other domains, thereby enhancing the reliability of the results.

5.2 Practical Implications

Drawing from the research outcomes, this study presents several managerial implications that are expected to benefit government agencies and other stakeholders engaged in the management of agri-food waste. For government, it requires more initiative or knowledge to foster the development of agri-food waste valorization. Firstly, it is highly crucial to enhance the government's governance capacity. The government should establish reasonable incentive mechanisms to ensure the service quality of fiscal funds in the field of agri-food waste valorization [67]. Therefore, the government should seize the opportunity of applying and promoting agri-food waste valorization to improve risk management and performance evaluation in the agricultural supply chain. Beyond financial investments, the government needs to leverage its influence and organizational capabilities to engage more stakeholders and jointly construct a technology-supported ecosystem for agri-food waste management. The digital waste management platform is expected to be positioned as a more solution-oriented approach, leveraging the integration of smart technologies in a practical and innovative manner to address environmental and social issues, thereby assisting governments and enterprises in making scientific decisions [68]. For supply chain members, they should also enhance information disclosure and technological innovation. The strategic integration of upstream and downstream enterprises in the supply chain is the first step. Cooperation with upstream enterprises with resource aggregation can greatly reduce the risks related to raw material supply [69], while cooperation with downstream enterprises with first-hand market information can reduce the risks of demand uncertainty. Secondly, as the immense operational pressures and high costs associated with adopting advanced technologies may hinder enterprises in technological innovation, a potential lightweight mitigation approach involves the training of current employees to collaborate with digital technology providers that offer modular solutions. These solutions can be rapidly scaled up and tested, thereby minimizing significant financial and operational risks[70]. For smart technology providers, it is recommended to adopt a platform-based business model rather than a product-centric one. The underlying logic of the platform business model underscores the necessity for technology providers to offer digital solutions not merely to enterprises involved in agri-food waste processing, but also to those engaged in agri-food waste recycling. By adhering to established data standards, it becomes feasible for data to traverse the entire waste management value chain with the waste stream, thereby facilitating end-to-end digitization[70].

5.3. Limitations and Future Research

Here are some limitations of this study: First, despite the author's diligent effort to review extant literature on the valorization of agri-food waste, it remains a challenge to encompass all the literature. Considering that some challenges exist in practice but there is limited literature research, the identified challenges may not be comprehensive. Future research could incorporate a broader range of empirical survey findings to address this gap. Secondly, the implementation and development of smart technology solutions in practice are intricate. Consequently, some of the proposed solutions in this study may lack sufficient details. Future research could delve deeper into the precise application of smart technologies in the realm of agri-food waste, conducting a more methodical analysis. Lastly, while this study operates within a Fermatean fuzzy framework, alternative methods for managing uncertainty could be explored, and the outcomes could be compared.

Author Contributions: Qing: Conceptualization, methodology, supervision. Hongjuan: Methodology, software, formal analysis, writing-original draft, visualization. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data generated in this study is available from the corresponding author on request.

Conflicts of Interest: The authors declare no conflicts of interest.

6 References

Basiry, M.; Surkan, P. J.; Ghosn, B.; Esmaillzadeh, A.; Azadbakht, L. Associations between Nutritional Deficiencies and Food Insecurity among Adolescent Girls: A Cross‐sectional Study. Food Sci. Nutr. 2024. https://doi.org/10.1002/fsn3.4065.

Amicarelli, V.; Lagioia, G.; Bux, C. Global Warming Potential of Food Waste through the Life Cycle Assessment: An Analytical Review. Environ. Impact Assess. Rev. 2021, 91 (106677), 106677. https://doi.org/10.1016/j.eiar.2021.106677.

Donno, D.; Turrini, F.; Farinini, E.; Mellano, M. G.; Boggia, R.; Beccaro, G. L.; Gamba, G. Chestnut Episperm as a Promising Natural Source of Phenolics from Agri-Food Processing by-Products: Optimisation of a Sustainable Extraction Protocol by Ultrasounds. Agriculture 2024, 14 (2), 246. https://doi.org/10.3390/agriculture14020246.

Hénault-Ethier, L.; Quinche, M.; Reid, B.; Hotte, N.; Fortin, A.; Normandin, É.; de La Rochelle Renaud, G.; Rasooli Zadeh, A.; Deschamps, M.-H.; Vandenberg, G. Opportunities and Challenges in Upcycling Agri-Food Byproducts to Generate Insect Manure (Frass): A Literature Review. Waste Manag. 2024, 176, 169‑191. https://doi.org/10.1016/j.wasman.2023.12.033.

Pavlić, B.; Aćimović, M.; Sknepnek, A.; Miletić, D.; Mrkonjić, Ž.; Kljakić, A. C.; Jerković, J.; Mišan, A.; Pojić, M.; Stupar, A.; Zeković, Z.; Teslić, N. Sustainable Raw Materials for Efficient Valorization and Recovery of Bioactive Compounds. Ind. Crops Prod. 2023, 193 (116167), 116167. https://doi.org/10.1016/j.indcrop.2022.116167.

Berenguer, C. V.; Andrade, C.; Pereira, J. A. M.; Perestrelo, R.; Câmara, J. S. Current Challenges in the Sustainable Valorisation of Agri-Food Wastes: A Review. Processes (Basel) 2022, 11 (1), 20. https://doi.org/10.3390/pr11010020.

Torres-Valenzuela, L. S.; Ballesteros-Gómez, A.; Rubio, S. Green Solvents for the Extraction of High Added-Value Compounds from Agri-Food Waste. Food Eng. Rev. 2020, 12 (1), 83‑100. https://doi.org/10.1007/s12393-019-09206-y.

Mak, T. M. W.; Xiong, X.; Tsang, D. C. W.; Yu, I. K. M.; Poon, C. S. Sustainable Food Waste Management towards Circular Bioeconomy: Policy Review, Limitations and Opportunities. Bioresour. Technol. 2020, 297 (122497), 122497. https://doi.org/10.1016/j.biortech.2019.122497.

Luo, N.; Olsen, T.; Liu, Y.; Zhang, A. Reducing Food Loss and Waste in Supply Chain Operations. Transp. Res. Part E: Logist. Trans. Rev. 2022, 162 (102730), 102730. https://doi.org/10.1016/j.tre.2022.102730.

Kassim, F. O.; Thomas, C. L. P.; Afolabi, O. O. D. Integrated Conversion Technologies for Sustainable Agri-Food Waste Valorization: A Critical Review. Biomass Bioenergy 2022, 156 (106314), 106314. https://doi.org/10.1016/j.biombioe.2021.106314.

Escudero-Curiel, S.; Giráldez, A.; Pazos, M.; Sanromán, Á. From Waste to Resource: Valorization of Lignocellulosic Agri-Food Residues through Engineered Hydrochar and Biochar for Environmental and Clean Energy Applications-A Comprehensive Review. Foods 2023, 12 (19). https://doi.org/10.3390/foods12193646.

Fatimah, Y. A.; Govindan, K.; Murniningsih, R.; Setiawan, A. Industry 4.0 Based Sustainable Circular Economy Approach for Smart Waste Management System to Achieve Sustainable Development Goals: A Case Study of Indonesia. J. Clean. Prod. 2020, 269 (122263), 122263. https://doi.org/10.1016/j.jclepro.2020.122263.

Foong, S. Y.; Chan, Y. H.; Lock, S. S. M.; Chin, B. L. F.; Yiin, C. L.; Cheah, K. W.; Loy, A. C. M.; Yek, P. N. Y.; Chong, W. W. F.; Lam, S. S. Microwave Processing of Oil Palm Wastes for Bioenergy Production and Circular Economy: Recent Advancements, Challenges, and Future Prospects. Bioresour. Technol. 2023, 369 (128478), 128478. https://doi.org/10.1016/j.biortech.2022.128478.

Tazikeh, S.; Zendehboudi, S.; Ghafoori, S.; Lohi, A.; Mahinpey, N. Algal Bioenergy Production and Utilization: Technologies, Challenges, and Prospects. J. Environ. Chem. Eng. 2022, 10 (3), 107863. https://doi.org/10.1016/j.jece.2022.107863.

Hassoun, A.; Aït-Kaddour, A.; Abu-Mahfouz, A. M.; Rathod, N. B.; Bader, F.; Barba, F. J.; Biancolillo, A.; Cropotova, J.; Galanakis, C. M.; Jambrak, A. R.; Lorenzo, J. M.; Måge, I.; Ozogul, F.; Regenstein, J. The Fourth Industrial Revolution in the Food Industry-Part I: Industry 4.0 Technologies. Crit. Rev. Food Sci. Nutr. 2023, 63 (23), 6547–6563. https://doi.org/10.1080/10408398.2022.2034735.

Bag, S.; Dhamija, P.; Singh, R. K.; Rahman, M. S.; Sreedharan, V. R. Big Data Analytics and Artificial Intelligence Technologies Based Collaborative Platform Empowering Absorptive Capacity in Health Care Supply Chain: An Empirical Study. J. Bus. Res. 2023, 154 (113315), 113315. https://doi.org/10.1016/j.jbusres.2022.113315.

Ciccullo, F.; Fabbri, M.; Abdelkafi, N.; Pero, M. Exploring the Potential of Business Models for Sustainability and Big Data for Food Waste Reduction. J. Clean. Prod. 2022, 340 (130673), 130673. https://doi.org/10.1016/j.jclepro.2022.130673.

Naruetharadhol, P.; Wongsaichia, S.; Pienwisetkaew, T.; Schrank, J.; Chaiwongjarat, K.; Thippawong, P.; Khotsombat, T.; Ketkaew, C. Consumer Intention to Utilize an E-Commerce Platform for Imperfect Vegetables Based on Health-Consciousness. Foods 2023, 12 (6). https://doi.org/10.3390/foods12061166.

Aniza, R.; Chen, W.-H.; Pétrissans, A.; Hoang, A. T.; Ashokkumar, V.; Pétrissans, M. A Review of Biowaste Remediation and Valorization for Environmental Sustainability: Artificial Intelligence Approach. Environ. Pollut. 2023, 324 (121363), 121363. https://doi.org/10.1016/j.envpol.2023.121363.

Tapia-Quirós, P.; Montenegro-Landívar, M. F.; Reig, M.; Vecino, X.; Cortina, J. L.; Saurina, J.; Granados, M. Recovery of Polyphenols from Agri-Food by-Products: The Olive Oil and Winery Industries Cases. Foods 2022, 11 (3). https://doi.org/10.3390/foods11030362.

Mannaa, M.; Mansour, A.; Park, I.; Lee, D.-W.; Seo, Y.-S. Insect-Based Agri-Food Waste Valorization: Agricultural Applications and Roles of Insect Gut Microbiota. Environ. Sci. Ecotechnol. 2024, 17 (100287), 100287. https://doi.org/10.1016/j.ese.2023.100287.

DeLay, N. D.; Thompson, N. M.; Mintert, J. R. Precision Agriculture Technology Adoption and Technical Efficiency. J. Agric. Econ. 2022, 73 (1), 195–219. https://doi.org/10.1111/1477-9552.12440.

Mondejar, M. E.; Avtar, R.; Diaz, H. L. B.; Dubey, R. K.; Esteban, J.; Gómez-Morales, A.; Hallam, B.; Mbungu, N. T.; Okolo, C. C.; Prasad, K. A.; She, Q.; Garcia-Segura, S. Digitalization to Achieve Sustainable Development Goals: Steps towards a Smart Green Planet. Sci. Total Environ. 2021, 794 (148539), 148539. https://doi.org/10.1016/j.scitotenv.2021.148539.

Santos, F. J.; Guzmán, C.; Ahumada, P. Assessing the Digital Transformation in Agri-Food Cooperatives and Its Determinants. J. Rural Stud. 2024, 105 (103168), 103168. https://doi.org/10.1016/j.jrurstud.2023.103168.

Abbate, S.; Centobelli, P.; Cerchione, R. The Digital and Sustainable Transition of the Agri-Food Sector. Technol. Forecast. Soc. Change 2023, 187 (122222), 122222. https://doi.org/10.1016/j.techfore.2022.122222.

Calafat-Marzal, C.; Sánchez-García, M.; Marti, L.; Puertas, R. Agri-Food 4.0: Drivers and Links to Innovation and Eco-Innovation. Comput. Electron. Agric. 2023, 207 (107700), 107700. https://doi.org/10.1016/j.compag.2023.107700.

Ancín, M.; Pindado, E.; Sánchez, M. New Trends in the Global Digital Transformation Process of the Agri-Food Sector: An Exploratory Study Based on Twitter. Agric. Syst. 2022, 203 (103520), 103520. https://doi.org/10.1016/j.agsy.2022.103520.

Vern, P.; Panghal, A.; Mor, R. S.; Kamble, S. S.; Islam, M. S.; Khan, S. A. R. Influential barriers to blockchain technology implementation in agri-food supply chain. Oper. Manage. Res. 2023, 16(3), 1206-1219.

Pakseresht, A.; Yavari, A.; Kaliji, S. A.; Hakelius, K. The Intersection of Blockchain Technology and Circular Economy in the Agri-Food Sector. Sustain. Prod. Consum. 2023, 35, 260–274. https://doi.org/10.1016/j.spc.2022.11.002.

Belhadi, A.; Kamble, S.; Subramanian, N.; Singh, R. K.; Venkatesh, M. Digital capabilities to manage agri-food supply chain uncertainties and build supply chain resilience during compounding geopolitical disruptions. Int. J. Oper. Prod. Man. 2024.

Trevisan, C.; Formentini, M. Digital Technologies for Food Loss and Waste Prevention and Reduction in Agri-Food Supply Chains: A Systematic Literature Review and Research Agenda. IEEE Trans. Eng. Manage. 2024, 1–20. https://doi.org/10.1109/tem.2023.3273110.

Riera, M. A.; Maldonado, S.; Palma, R. Multicriteria Analysis and GIS Applied to the Selection of agri-industrial Waste. A Case Study Contextualized to the Ecuadorian Reality. J. Clean. Prod. 2023, 429 (139505), 139505. https://doi.org/10.1016/j.jclepro.2023.139505.

Gao, F.; Han, M.; Wang, S.; Gao, J. A Novel Fermatean Fuzzy BWM-VIKOR Based Multi-Criteria Decision-Making Approach for Selecting Health Care Waste Treatment Technology. Eng. Appl. Artif. Intell. 2024, 127 (107451), 107451. https://doi.org/10.1016/j.engappai.2023.107451.

Çelik, S.; Peker, İ.; Gök-Kısa, A. C.; Büyüközkan, G. Multi-Criteria Evaluation of Medical Waste Management Process under Intuitionistic Fuzzy Environment: A Case Study on Hospitals in Turkey. Socioecon. Plann. Sci. 2023, 86 (101499), 101499. https://doi.org/10.1016/j.seps.2022.101499.

Komal. Archimedean T-Norm and t-Conorm Based Intuitionistic Fuzzy WASPAS Method to Evaluate Health-Care Waste Disposal Alternatives with Unknown Weight Information. Appl. Soft Comput. 2023, 146 (110751), 110751. https://doi.org/10.1016/j.asoc.2023.110751.

Kabirifar, K.; Ashour, M.; Yazdani, M.; Mahdiyar, A.; Malekjafarian, M. Cybernetic-parsimonious MCDM modeling with application to the adoption of Circular Economy in waste management. Appl. Soft. Comput. 2023, 139, 110186.

Karuppiah, K.; Sankaranarayanan, B. An integrated multi-criteria decision-making approach for evaluating e-waste mitigation strategies. Appl. Soft. Comput. 2023, 144, 110420.

Kayapinar Kaya, S.; Erginel, N. Futuristic Airport: A Sustainable Airport Design by Integrating Hesitant Fuzzy SWARA and Hesitant Fuzzy Sustainable Quality Function Deployment. J. Clean. Prod. 2020, 275 (123880), 123880. https://doi.org/10.1016/j.jclepro.2020.123880.

Kutlu Gündoğdu, F.; Kahraman, C. A Novel Spherical Fuzzy QFD Method and Its Application to the Linear Delta Robot Technology Development. Eng. Appl. Artif. Intell. 2020, 87 (103348), 103348. https://doi.org/10.1016/j.engappai.2019.103348.

Senapati, T.; Yager, R. R. Fermatean Fuzzy Sets. J. Ambient Intell. Humaniz. Comput. 2020, 11 (2), 663–674. https://doi.org/10.1007/s12652-019-01377-0.

Lim, W. M.; Yap, S.-F.; Makkar, M. Home Sharing in Marketing and Tourism at a Tipping Point: What Do We Know, How Do We Know, and Where Should We Be Heading? J. Bus. Res. 2021, 122, 534–566. https://doi.org/10.1016/j.jbusres.2020.08.051.

Aydoğan, H.; Ozkir, V. A Fermatean Fuzzy MCDM Method for Selection and Ranking Problems: Case Studies. Expert Syst. Appl. 2024, 237 (121628), 121628. https://doi.org/10.1016/j.eswa.2023.121628.

Deveci, M.; Varouchakis, E. A.; Brito-Parada, P. R.; Mishra, A. R.; Rani, P.; Bolgkoranou, M.; Galetakis, M. Evaluation of Risks Impeding Sustainable Mining Using Fermatean Fuzzy Score Function Based SWARA Method. Appl. Soft Comput. 2023, 139 (110220), 110220. https://doi.org/10.1016/j.asoc.2023.110220.

Akhanova, G.; Nadeem, A.; Kim, J. R.; Azhar, S. A Multi-Criteria Decision-Making Framework for Building Sustainability Assessment in Kazakhstan. Sustain. Cities Soc. 2020, 52 (101842), 101842. https://doi.org/10.1016/j.scs.2019.101842.

Karuppiah, K.; Sankaranarayanan, B.; Ali, S. M.; AlArjani, A.; Mohamed, A. Causality Analytics among Key Factors for Green Economy Practices: Implications for Sustainable Development Goals. Front. Environ. Sci. 2022, 10. https://doi.org/10.3389/fenvs.2022.933657.

Huang, H.-C.; Huang, C.-N.; Lo, H.-W.; Thai, T.-M. Exploring the Mutual Influence Relationships of International Airport Resilience Factors from the Perspective of Aviation Safety: Using Fermatean Fuzzy DEMATEL Approach. Axioms 2023, 12 (11), 1009. https://doi.org/10.3390/axioms12111009.

Lan, Z.; Pau, K.; Mohd Yusof, H.; Huang, X. Hierarchical Topological Model of the Factors Influencing Adolescents' Non-Suicidal Self-Injury Behavior Based on the DEMATEL-TAISM Method. Sci. Rep. 2022, 12 (1), 17238. https://doi.org/10.1038/s41598-022-21377-z.

Alshahrani, R.; Yenugula, M.; Algethami, H.; Alharbi, F.; Shubhra Goswami, S.; Noorulhasan Naveed, Q.; Lasisi, A.; Islam, S.; Khan, N. A.; Zahmatkesh, S. Establishing the Fuzzy Integrated Hybrid MCDM Framework to Identify the Key Barriers to Implementing Artificial Intelligence-Enabled Sustainable Cloud System in an IT Industry. Expert Syst. Appl. 2024, 238 (121732), 121732. https://doi.org/10.1016/j.eswa.2023.121732.

Seker, S.; Aydin, N. Fermatean Fuzzy Based Quality Function Deployment Methodology for Designing Sustainable Mobility Hub Center. Appl. Soft Comput. 2023, 134 (110001), 110001. https://doi.org/10.1016/j.asoc.2023.110001.

Khoshsepehr, Z.; Alinejad, S.; Alimohammadlou, M. Exploring Industrial Waste Management Challenges and Smart Solutions: An Integrated Hesitant Fuzzy Multi-Criteria Decision-Making Approach. J. Clean. Prod. 2023, 420 (138327), 138327. https://doi.org/10.1016/j.jclepro.2023.138327.

Xiang, W.; Gao, J. Do Not Be Anticlimactic: Farmers' Behavior in the Sustainable Application of Green Agricultural Technology−A Perceived Value and Government Support Perspective. Agriculture 2023, 13 (2), 247. https://doi.org/10.3390/agriculture13020247.

Yin, Q.; Wang, Q.; Du, M.; Wang, F.; Sun, W.; Chen, L.; Tang, H. Promoting the resource utilization of agricultural wastes in China with public-private-partnership mode: An evolutionary game perspective. J. Clean. Prod. 2024, 434, 140206.

Zhang, A.; Venkatesh, V. G.; Wang, J. X.; Mani, V.; Wan, M.; Qu, T. Drivers of Industry 4.0-Enabled Smart Waste Management in Supply Chain Operations: A Circular Economy Perspective in China. Prod. Plan. Control 2023, 34 (10), 870‑886. https://doi.org/10.1080/09537287.2021.1980909.

Somorin, T.; Campos, L. C.; Kinobe, J. R.; Kulabako, R. N.; Afolabi, O. O. D. Sustainable Valorisation of Agri-Food Waste from Open-Air Markets in Kampala, Uganda via Standalone and Integrated Waste Conversion Technologies. Biomass Bioenergy 2023, 172 (106752), 106752. https://doi.org/10.1016/j.biombioe.2023.106752.

Timmis, K.; Verstraete, W.; Regina, V. R.; Hallsworth, J. E. The Pareto principle: To what extent does it apply to resource acquisition in stable microbial communities and thereby steer their geno‑/eco-type compositions and interactions between their members?. Environ. Microbiol. 2023, 25(7), 1221-1231.

Rehman, F. U.; Al-Ghazali, B. M.; Farook, M. R. M. Interplay in Circular Economy Innovation, Business Model Innovation, SDGs, and Government Incentives: A Comparative Analysis of Pakistani, Malaysian, and Chinese SMEs. Sustainability 2022, 14 (23), 15586. https://doi.org/10.3390/su142315586.

Feldman, J.; Seligmann, H.; King, S.; Flynn, M.; Shelley, T.; Helwig, A.; Burey, P. (polly). Circular Economy Barriers in Australia: How to Translate Theory into Practice? Sustain. Prod. Consum. 2024, 45, 582–597. https://doi.org/10.1016/j.spc.2024.02.001.

Donner, M.; Verniquet, A.; Broeze, J.; Kayser, K.; De Vries, H. Critical Success and Risk Factors for Circular Business Models Valorising Agricultural Waste and By-Products. Resour. Conserv. Recycl. 2021, 165 (105236), 105236. https://doi.org/10.1016/j.resconrec.2020.105236.

Ju, Y.; Cheng, Y.; Chen, L.; Xing, X. Enhancing firms' innovation persistence in the circular economy through government-supported green supply chain demonstrations: cost leadership or differentiation?. Int. J. Logist-Res. App. 2024, 1-21.

Medaglia, R.; Rukanova, B.; Zhang, Z. Digital government and the circular economy transition: An analytical framework and a research agenda. Gov. Inform. Q. 2024, 41(1), 101904.

Nargotra, P.; Sharma, V.; Tsai, M. L.; Hsieh, S. L.; Dong, C. D.; Wang, H. M. D.; Kuo, C. H. Recent advancements in the valorization of agri-industrial food waste for the production of nanocellulose. Appl. Sci-Basel. 2023, 13(10), 6159.

Boateng, I. D. Mechanisms, capabilities, limitations, and economic stability outlook for extracting phenolics from agri-byproducts using emerging thermal extraction technologies and their combinative effects. Food. Bioprocess. Tech. 2023, 1-32.

Figge, F.; Thorpe, A.; Gutberlet, M. Definitions of the circular economy-circularity matters. Ecol. Econ. 2023, 208.

Punia Bangar, S.; Chaudhary, V.; Kajla, P.; Balakrishnan, G.; Phimolsiripol, Y. Strategies for Upcycling Food Waste in the Food Production and Supply Chain. Trends Food Sci. Technol. 2024, 143 (104314), 104314. https://doi.org/10.1016/j.tifs.2023.104314.

Aschemann-Witzel, J.; Asioli, D.; Banovic, M.; Perito, M. A.; Peschel, A. O.; Stancu, V. Defining Upcycled Food: The Dual Role of Upcycling in Reducing Food Loss and Waste. Trends Food Sci. Technol. 2023, 132, 132–137. https://doi.org/10.1016/j.tifs.2023.01.001.

Annosi, M. C.; Brunetta, F.; Bimbo, F.; Kostoula, M. Digitalization within Food Supply Chains to Prevent Food Waste. Drivers, Barriers and Collaboration Practices. Ind. Mark. Manag. 2021, 93, 208–220. https://doi.org/10.1016/j.indmarman.2021.01.005.

Tian, M.; Liu, R.; Wang, J.; Liang, J.; Nian, Y.; Ma, H. How to promote the sustainability of China's rural waste management system: Increase government subsidies or increase waste service management fees?. Nat. Resour. Forum. 2024.

Razip, M. M.; Savita, K. S.; Kalid, K. S.; Ahmad, M. N.; Zaffar, M.; Abdul Rahim, E. E.; Baleanu, D.; Ahmadian, A. The Development of Sustainable IoT E-Waste Management Guideline for Households. Chemosphere 2022, 303 (Pt 1), 134767. https://doi.org/10.1016/j.chemosphere.2022.134767.

Abu Seman, N. A.; Govindan, K.; Mardani, A.; Zakuan, N.; Mat Saman, M. Z.; Hooker, R. E.; Ozkul, S. The Mediating Effect of Green Innovation on the Relationship between Green Supply Chain Management and Environmental Performance. J. Clean. Prod. 2019, 229, 115–127. https://doi.org/10.1016/j.jclepro.2019.03.211.

Borchard, R.; Zeiss, R.; Recker, J. Digitalization of Waste Management: Insights from German Private and Public Waste Management Firms. Waste Manag. Res. 2022, 40 (6), 775–792. https://doi.org/10.1177/0734242X211029173.

Amado, M.; Barca, C.; Hernández, M. A.; Ferrasse, J.-H. Evaluation of Energy Recovery Potential by Anaerobic Digestion and Dark Fermentation of Residual Biomass in Colombia. Front. Energy Res. 2021, 9. https://doi.org/10.3389/fenrg.2021.690161.

Arshad, R. N.; Abdul-Malek, Z.; Roobab, U.; Qureshi, M. I.; Khan, N.; Ahmad, M. H.; Liu, Z.-W.; Aadil, R. M. Effective Valorization of Food Wastes and By‐products through Pulsed Electric Field: A Systematic Review. J. Food Process Eng. 2021, 44 (3). https://doi.org/10.1111/jfpe.13629.

Gomathi, S.; Rameshpathy, M. Valorization of agri-Waste Residues into Bio-Vanillin a Comprehensive Review. Ind. Crops Prod. 2023, 205 (117522), 117522. https://doi.org/10.1016/j.indcrop.2023.117522.

Vilas-Boas, A. A.; Pintado, M.; Oliveira, A. L. S. Natural Bioactive Compounds from Food Waste: Toxicity and Safety Concerns. Foods 2021, 1564.

Nolasco, A.; Squillante, J.; Velotto, S.; D'Auria, G.; Ferranti, P.; Mamone, G.; Errico, M. E.; Avolio, R.; Castaldo, R.; Cirillo, T.; Esposito, F. Valorization of Coffee Industry Wastes: Comprehensive Physicochemical Characterization of Coffee Silverskin and Multipurpose Recycling Applications. J. Clean. Prod. 2022, 370 (133520), 133520. https://doi.org/10.1016/j.jclepro.2022.133520.

Mármol, I.; Quero, J.; Ibarz, R.; Ferreira-Santos, P.; Teixeira, J. A.; Rocha, C. M. R.; Pérez-Fernández, M.; García-Juiz, S.; Osada, J.; Martín-Belloso, O.; Rodríguez-Yoldi, M. J. Valorization of agri-Food by-Products and Their Potential Therapeutic Applications. Food Bioprod. Process. 2021, 128, 247–258. https://doi.org/10.1016/j.fbp.2021.06.003.

Bayat, H.; Dehghanizadeh, M.; Jarvis, J. M.; Brewer, C. E.; Jena, U. Hydrothermal Liquefaction of Food Waste: Effect of Process Parameters on Product Yields and Chemistry. Front. Sustain. Food. S. 2021, 5, 658592.

Castro-Muñoz, R.; Díaz-Montes, E.; Gontarek-Castro, E.; Boczkaj, G.; Galanakis, C. M. A Comprehensive Review on Current and Emerging Technologies toward the Valorization of Bio-Based Wastes and by Products from Foods. Compr. Rev. Food Sci. Food Saf. 2022, 21 (1), 46–105. https://doi.org/10.1111/1541-4337.12894.

García-Sánchez, M. E.; Universidad de Guadalajara; Robledo-Ortiz, J. R.; Jiménez-Palomar, I.; González-Reynoso, O.; González-García, Y. Production of Bacterial Cellulose by Komagataeibacter Xylinus Using Mango Waste as Alternative Culture Medium. Rev. Mex. Ing. Quim. 2019, 19 (2), 851–865. https://doi.org/10.24275/rmiq/bio743.

Pienwisetkaew, T.; Wongsaichia, S.; Pinyosap, B.; Prasertsil, S.; Poonsakpaisarn, K.; Ketkaew, C. The behavioral intention to adopt circular economy-based digital technology for agricultural waste valorization. Foods 2023, 12(12), 2341.

Elkatry, H. O.; El-Beltagi, H. S.; Ahmed, A. R.; Mohamed, H. I.; Al-Otaibi, H. H.; Ramadan, K. M. A.; Mahmoud, M. A. A. The Potential Use of Indian Rice Flour or Husk in Fortification of Pan Bread: Assessing Bread's Quality Using Sensory, Physicochemical, and Chemometric Methods. Front. Nutr. 2023, 10, 1240527. https://doi.org/10.3389/fnut.2023.1240527.

Bangar, S. P.; Chaudhary, V.; Kajla, P.; Balakrishnan, G.; Phimolsiripol, Y. Strategies for Upcycling Food Waste in the Food Production and Supply Chain. Trends Food Sci. Tech. 2024, 143.

Tura, N.; Hanski, J.; Ahola, T.; Ståhle, M.; Piiparinen, S.; Valkokari, P. Unlocking Circular Business: A Framework of Barriers and Drivers. J. Clean. Prod. 2019, 212, 90–98. https://doi.org/10.1016/j.jclepro.2018.11.202.

Caraballo, M.; Rohm, S.; Struck, H. Green Solvents for Deoiling Pumpkin and Sunflower Press Cakes: Impact on Composition and Technofunctional Properties. Int. J. Food Sci. Tech. 2023, 58 (4), 1931–1939.

Cassoni, A. C.; Costa, P.; Vasconcelos, M. W.; Pintado, M. Systematic Review on Lignin Valorization in the agri-Food System: From Sources to Applications. J. Environ. Manage. 2022, 317 (115258), 115258. https://doi.org/10.1016/j.jenvman.2022.115258.

Romano, R.; De Luca, L.; Aiello, A.; Rossi, D.; Pizzolongo, F.; Masi, P. Bioactive Compounds Extracted by Liquid and Supercritical Carbon Dioxide from Citrus Peels. Int. J. Food Sci. Technol. 2022, 57 (6), 3826–3837. https://doi.org/10.1111/ijfs.15712.

Azinheiro, S.; Carvalho, J.; Prado, M.; Garrido-Maestu, A. Application of Recombinase Polymerase Amplification with Lateral Flow for a Naked-Eye Detection of Listeria Monocytogenes on Food Processing Surfaces. Foods 2020, 9 (9). https://doi.org/10.3390/foods9091249.

Mikucka, W.; Witońska, I.; Zielińska, M.; Bułkowska, K.; Binczarski, M. Concept for the Valorization of Cereal Processing Waste: Recovery of Phenolic Acids by Using Waste-Derived Tetrahydrofurfuryl Alcohol and Biochar. Chemosphere 2023, 313 (137457), 137457. https://doi.org/10.1016/j.chemosphere.2022.137457.

Donner, M.; Verniquet, A.; Broeze, J.; Kayser, K.; De Vries, H. Critical Success and Risk Factors for Circular Business Models Valorising Agricultural Waste and By-Products. Resour. Conserv. Recycl. 2021, 165 (105236), 105236. https://doi.org/10.1016/j.resconrec.2020.105236.

Alaba, P. A.; Popoola, S. I.; Abnisal, F.; Lee, C. S.; Ohunakin, O. S.; Adetiba, E.; Akanle, M. B.; Abdul Patah, M. F.; Atayero, A. A. A.; Wan Daud, W. M. A. Thermal Decomposition of Rice Husk: A Comprehensive Artificial Intelligence Predictive Model. J. Therm. Anal. Calorim. 2020, 140 (4), 1811‑1823. https://doi.org/10.1007/s10973-019-08915-0.

Olabi, A. G.; Nassef, A. M.; Rodriguez, C.; Abdelkareem, M. A.; Rezk, H. Application of Artificial Intelligence to Maximize Methane Production from Waste Paper. Int. J. Energy Res. 2020, 44 (12), 9598‑9608. https://doi.org/10.1002/er.5446.

Jiang, Y.; Huang, J.; Luo, W.; Chen, K.; Yu, W.; Zhang, W.; Huang, C.; Yang, J.; Huang, Y. Prediction for Odor Gas Generation from Domestic Waste Based on Machine Learning. Waste Manag. 2023, 156, 264‑271. https://doi.org/10.1016/j.wasman.2022.12.006.

Izquierdo-Horna, L.; Damazo, M.; Yanayaco, D. Identification of Urban Sectors Prone to Solid Waste Accumulation: A Machine Learning Approach Based on Social Indicators. Comput. Environ. Urban 2022, 96, 101834..

Tseng, M.-L.; Tran, T. P. T.; Ha, H. M.; Bui, T.-D.; Lim, M. K. Causality of Circular Business Strategy under Uncertainty: A Zero-Waste Practices Approach in Seafood Processing Industry in Vietnam. Resour. Conserv. Recycl. 2022, 181 (106263), 106263. https://doi.org/10.1016/j.resconrec.2022.106263.

Astill, J.; Dara, R. A.; Campbell, M.; Farber, J. M.; Fraser, E. D. G.; Sharif, S.; Yada, R. Y. Transparency in Food Supply Chains: A Review of Enabling Technology Solutions. Trends Food Sci. Technol. 2019, 91, 240‑247. https://doi.org/10.1016/j.tifs.2019.07.024.

Liegeard, J.; Manning, L. Use of Intelligent Applications to Reduce Household Food Waste. Crit. Rev. Food Sci. Nutr. 2020, 60 (6), 1048‑1061. https://doi.org/10.1080/10408398.2018.1556580.

Zhu, J.; Luo, Z.; Liu, Y.; Tong, H.; Yin, K. Environmental Perspectives for Food Loss Reduction via Smart Sensors: A Global Life Cycle Assessment. J. Clean. Prod. 2022, 374 (133852), 133852. https://doi.org/10.1016/j.jclepro.2022.133852.

Garcia Millan, V. E.; Rankine, C.; Sanchez-Azofeifa, G. A. Crop Loss Evaluation Using Digital Surface Models from Unmanned Aerial Vehicles Data. Remote Sens. (Basel) 2020, 12 (6), 981. https://doi.org/10.3390/rs12060981.

Iost Filho, F. H.; Heldens, W. B.; Kong, Z.; de Lange, E. S. Drones: Innovative Technology for Use in Precision Pest Management. J. Econ. Entomol. 2020, 113 (1), 1 – 25. https://doi.org/10.1093/jee/toz268.

Ciccullo, F.; Cagliano, R.; Bartezzaghi, G.; Perego, A. Implementing the Circular Economy Paradigm in the Agri-Food Supply Chain: The Role of Food Waste Prevention Technologies. Resour. Conserv. Recycl. 2021, 164 (105114), 105114. https://doi.org/10.1016/j.resconrec.2020.105114.

Liu, X.; Le Bourvellec, C.; Yu, J.; Zhao, L.; Wang, K.; Tao, Y.; Renard, C. M. G. C.; Hu, Z. Trends and Challenges on Fruit and Vegetable Processing: Insights into Sustainable, Traceable, Precise, Healthy, Intelligent, Personalized and Local Innovative Food Products. Trends Food Sci. Technol. 2022, 125, 12–25. https://doi.org/10.1016/j.tifs.2022.04.016.

Silva, N. D. S.; De Souza Farias, F.; Dos Santos Freitas, M. M.; Hernández, E. J. G. P.; Dantas, V. V.; Oliveira, M. E. C.; Lourenço. Artificial Intelligence Application for Classification and Selection of Fish Gelatin Packaging Film Produced with Incorporation of Palm Oil and Plant Essential Oils. Food Packaging Shelf 2021, 27.

Yang, F.; Guo, H.; Gao, P.; Yu, D.; Xu, Y.; Jiang, Q.; Yu, P.; Xia, W. Comparison of Methodological Proposal in Sensory Evaluation for Chinese Mitten Crab (Eriocheir Sinensis) by Data Mining and Sensory Panel. Food Chem. 2021, 356 (129698), 129698. https://doi.org/10.1016/j.foodchem.2021.129698.

Tian, C.; Luan, W.; Li, S.; Xue, Y.; Jin, X. Spatial Imbalance of Chinese Seafood Restaurants and Its Relationship with Socioeconomic Factors. Ocean Coast. Manag. 2021, 211 (105764), 105764. https://doi.org/10.1016/j.ocecoaman.2021.105764.

Patroni, J.; von Briel, F.; Recker, J. Unpacking the Social Media–Driven Innovation Capability: How Consumer Conversations Turn into Organizational Innovations. Inf. Manag. 2022, 59 (3), 103267. https://doi.org/10.1016/j.im.2020.103267.

Prapti, D. R.; Mohamed Shariff, A. R.; Che Man, H.; Ramli, N. M.; Perumal, T.; Shariff, M. Internet of Things (IoT) – based Aquaculture: An Overview of IoT Application on Water Quality Monitoring. Rev. Aquac. 2022, 14 (2), 979–992. https://doi.org/10.1111/raq.12637.

Huan, J.; Li, H.; Wu, F.; Cao, W. Design of Water Quality Monitoring System for Aquaculture Ponds Based on NB-IoT. Aquacult. Eng. 2020, 90 (102088), 102088. https://doi.org/10.1016/j.aquaeng.2020.102088.

Friha, O.; Ferrag, M. A.; Shu, L.; Maglaras, L.; Wang, X. Internet of Things for the Future of Smart Agriculture: A Comprehensive Survey of Emerging Technologies. IEEE/CAA J. Autom. Sin. 2021, 8 (4), 718–752. https://doi.org/10.1109/jas.2021.1003925.

Barbut, S. Meat Industry 4.0: A Distant Future? Anim. Front. 2020, 10 (4), 38 – 47. https://doi.org/10.1093/af/vfaa038.

Bader, F.; Rahimifard, S. A Methodology for the Selection of Industrial Robots in Food Handling. Innov. Food Sci. Emerg. Technol. 2020, 64 (102379), 102379. https://doi.org/10.1016/j.ifset.2020.102379.

Duong, L. N. K.; Al-Fadhli, M.; Jagtap, S.; Bader, F.; Martindale, W.; Swainson, M.; Paoli, A. A Review of Robotics and Autonomous Systems in the Food Industry: From the Supply Chains Perspective. Trends Food Sci. Technol. 2020, 106, 355–364. https://doi.org/10.1016/j.tifs.2020.10.028.

Defraeye, T.; Shrivastava, C.; Berry, T.; Verboven, P.; Onwude, D.; Schudel, S.; Rossi, R. M. Digital Twins Are Coming: Will We Need Them in Supply Chains of Fresh Horticultural Produce? Trends Food Sci. Tech. 2021, 109, 245–258.