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Review

The complexities of decision-making in food waste valorization: A critical review

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ABSTRACT

The efficient utilization of food waste (FW) resources through Food Waste Valorization (FWV) has received increasing attention in recent years. Various decision-making studies have been undertaken to facilitate FWV implementation, such as the studies on decision-making framework and FWV technology assessment. Food waste hierarchy is a widely discussed framework in FW management, but it was found too simplified and does not always contribute positively to environmental sustainability. Moreover, decision-making studies in FWV often focus on specific aspects of the food system and employ distinctive decision-making approaches, making it difficult to compare the results from different studies. Therefore, our literature review is conducted to provide a comprehensive understanding of FWV decision-making. This study identifies what decisions are needed, and three levels of decisions are revealed: system-level, FW stream-level, and FWV option-level. The assessment approaches and criteria used to support decision-making in FWV are also collected and analyzed. Building upon these findings, an hourglass model is synthesized to provide a holistic illustration of decision-making in FWV. This study untangles the complexities of FWV decision-making and sheds light on the limitations of current studies. We anticipate this study will make more people realize that FWV is a multidisciplinary issue and requires the collective participation of researchers, practitioners, policymakers, and consumers. Such collective engagement is essential to effectively address practical challenges and propel the transition of the current food system toward a more resource-efficient paradigm.

1. Introduction

Food loss and waste have emerged as pressing concerns due to their detrimental impact on sustainability. According to UN Environment Programme (UNEP), around 14 percent of food is lost before reaching the market every year, which is associated with 1.5 gigatons of CO_2 equivalent (UNEP, 2020). Meanwhile, around 17 percent of food is wasted at the end of the food supply chain every year (FAO, 2022). It was estimated that the average environmental footprint embedded in food waste generated per person per day is about 124 g CO_2 equivalent (Chen et al., 2020). Food loss and waste also lead to other environmental problems, such as water eutrophication, arable land depletion, and biodiversity loss (FAO, 2014). The economic and social consequences are also severe, including reduced incomes for farmers and a direct threat to food security (Papargyropoulou et al., 2014). To tackle this critical issue, many countries (BDO, 2020; Mubita et al., 2021; WRAP, 2017), regions (European Union, 2020), cities (Gemeente Amsterdam, 2020), and stakeholders in industries and catering services (Clowes et al., 2018; Stone et al., 2020) started to implement solutions to reduce food loss and waste.

Food Waste Valorization (FWV) is an emerging solution inspired by the Circular Economy (CE) to realize a sustainable food system (Jurgilevich et al., 2016; Papargyropoulou et al., 2014; Teigiserova et al., 2020). Building upon the waste hierarchy from CE, Papargyropoulou et al. (2014) initially proposed a comprehensive food waste hierarchy (Fig. 1) to guide the decision-making in Food Waste (FW) management. Expanding on this, Garcia-Garcia et al. (2017) introduced a more specific food waste hierarchy that encompasses various options for valorizing FW, including reusing it as animal feed, extracting valuable compounds, utilizing anaerobic digestion, etc. These options are classified under the categories of "reduce," "reuse," "recycle/recover," and

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List of abbreviations

FWV	Food Waste Valorization
CE	Circular Economy
FW	food waste
DSA-FWV	Decision Support Approaches for Food Waste Valorization
MCDA	Multi-criteria Decision Analysis
LCA	Life Cycle Assessment
SWOT	Strengths, Weaknesses, Opportunities, and Threats
LCC	Life Cycle Cost

"dispose," and their prioritization is determined according to the food waste hierarchy (Garcia-Garcia et al., 2017; Papargyropoulou et al., 2014).

Food waste hierarchy is a widely used framework to guide the decision-making in FWV (Garcia-Garcia et al., 2017; Papargyropoulou et al., 2014). However, an increasing number of studies demonstrated that the hierarchy cannot reflect the rank of sustainability performance. For example, Scherhaufer et al. (2020) concluded that the conversion to food ingredients, which is a high-level option in food waste hierarchy, does not always result in reduced environmental net impacts; Slorach et al. (2020a,b) found composting is worse than incineration and landfilling considering food-energy-water nexus, although composting was preferred over incineration and landfill in the food waste hierarchy. Parsa et al. (2023) concluded from their study that the food waste hierarchy is too simplified and failed to guide FW management, especially from the environmental sustainability perspective. The nature of FW added more complexity to the decision-making in FWV. Unlike other durable resources (e.g., metal, non-biodegradable plastic, construction material) widely discussed in CE, food loss and waste are biodegradable and generated throughout the entire food supply chain, changing rapidly in composition and quality compared to durable resources (Dong et al., 2022; Tedesco et al., 2021). Therefore, extending the life cycle of food loss and waste via FWV requires additional resources, indicating that FWV does not necessarily contribute positively to environmental sustainability (Scherhaufer et al., 2020).

Besides food waste hierarchy, a wide range of studies has been conducted to support and enhance decision-making in FWV, leading to diverse decision-support approaches for FWV (DSA-FWV). These studies covered multiple aspects of FWV decision-making, such as the context analysis to prioritize waste streams or regions (FAO, 2013; Xue et al., 2021), the indicator development to help decision-makers better understand the status quo and the performance of FWV (D'Adamo et al., 2020; Hoehn et al., 2021), the sustainability performance evaluation of alternative scenarios (Garcia-Garcia et al., 2019; Mondello et al., 2017; Patrizi et al., 2020), and the formulation of decision-making strategies (Feiz and Ammenberg, 2017; Laso et al., 2018; Manfredi and Cristobal, 2016; Stone et al., 2019). However, in this research area, most studies tend to take an individual perspective via case studies, upon which they are prone to address only part of the overall decision-making puzzle. The diverse system boundaries and diverse DSA-FWV result in several issues in advancing this research area. For example, decision-makers cannot compare the performance of different FWV strategies due to the different system boundaries and criteria, thus, they have to repeatedly evaluate the same valorization technologies (e.g., Khoo et al., 2009; Woon et al., 2016). It is also difficult for decision-makers to position their work into the whole FWV system, which may lead to the ignorance of critical decision factors and burden shifts to other stakeholders or food value chain stages.

To address these issues, this study undertakes a critical literature review to address two key questions: (1) What decisions are relevant in the context of FWV decision-making, and how do they connect (Section 3.1)? (2) What decision-support approaches (Section 3.2) and indicators (Section 3.3) have been employed to facilitate decision-making in FWV? After answering these questions, this study aims to identify an overall decision layout for FWV decision-making, which can help untangle the complexity of FWV decision-making (Section 3.3). This study intended to pave the way for future studies to generalize a holistic FWV decision-making guideline, which may further foster interconnections and facilitate progress and collaboration among scholars and practitioners in the field.

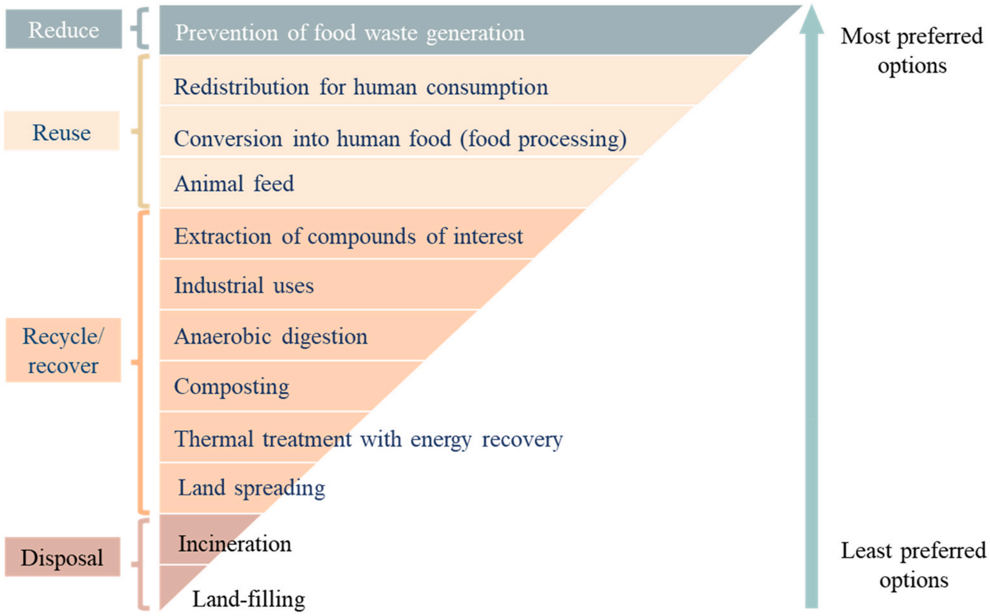

Fig. 1. Waste hierarchy for surplus food and food waste (Food waste hierarchy), adapted from Garcia-Garcia et al. (2017). "Conversion into human food (food processing)" is added between "redistribution for human consumption" and "animal feed" to further comprehend the food waste hierarchy.

2. Methodology

2.1. Literature search

A critical literature review was conducted in a systematic approach to achieve our research objectives. The review was conducted on the topic of decision-making in FWV, including performance assessment and decision-making practices. In this study, FWV refers to the options that are classified as reuse, recycle, and recover (Fig. 1). The keywords were selected from the terms commonly used in relevant studies. Boolean operators "AND" and "OR" were applied to the search string. We segmented the keywords into four groups:

Group 1 (food loss and waste): "food waste" OR "food loss" OR "food residues" OR "food side stream" OR "Food side flow" OR "vegetable waste" OR "fruit waste" OR "meat waste" OR "food by-product"

Group 2 (valorization): "valorization" OR "valorization" OR "circular*" OR "recovery" OR "recycling" OR "resource efficien*"

Group 3 (framework): "framework" OR "model" OR "tool" OR "method*" OR "guidance" OR "infrastructure" OR "system" OR "route" OR "strateg*" OR "approach" OR "option*"

Group 4 (evaluate): "assess*" OR "evalua*" OR "quantif*" OR "analys*" OR "estimat*" OR "calculat*" OR "measure*" OR "compar*"

To screen out the studies related to mathematical models, kinetic models/parameters, human behaviors, meta-analysis, logistics optimization, genetic engineering (e.g., for improving FW valorization such as bioplastic production), municipal solid waste that includes but is not limited to FW, and the optimization of FWV technologies, the following exclusion string was applied:

"kinetic*" OR "mathematic*" OR "behavi*" OR "Meta-analysis" OR "logistic*" OR "genetic*" OR "solid waste" OR ("condition*" AND ("improve*" OR "optimiz*"))

The literature search[1] was performed via the Web of Science, and the search was limited to English articles published between 2010 and 2022 (Access date: Oct 11, 2023).

2.2. Literature screen

The initial search turned up 946 articles. By reading the title and abstract, our first screening excluded four types of articles that are irrelevant to our main research goal.

1) The articles that mention resources or biomass or biowaste but do not mention FW.
2) The articles focus solely on technologies, such as the review of FWV technologies and the improvement of technologies.
3) The articles about assessment approaches but not for FWV.
4) The articles focus on the demonstration of FW reduction or valorization practices.

2.3. Data extraction and analysis

The overall methodology approach of this paper is shown in Fig. 2. To answer our research questions, we focused on the research objectives and methodologies in the literature. From the research objectives, we analyzed what kind of information (decision-making elements) is needed to support the decisions. Subsequently, we established a classification matrix for the key elements in FWV decision-making by analyzing the commonalities and grouping the literature accordingly (see Section 3.1 and Fig. S1). Then the methodologies were collected to understand how those decisions were made. These methodologies are referred to as DSA-FWV in this study. In Section 3.2, we paid particular attention to the performance assessment. The commonalities and diversities of the assessment approaches are detailed by comparing the methodological specifications they employed, the decision levels they involved, and the sustainability aspects they measured. In Section 3.3, we further reviewed the indicators/criteria used in the assessment to help decision-makers better understand and make choices among the indicators/criteria, as we noticed that diverse indicators are available but some of them measure similar things. With a thorough understanding of the decision-making process in FWV, in Section 3.4, we synthesized an hourglass model to outline a layout for the FWV decision-making process.

3. Results and discussion

The initial search spawned 946 articles. After the first screening, we excluded 757 articles that were irrelevant to our main subject and obtained 189 articles. In addition, four articles from the reference of obtained articles were added. In total, 193 articles were found relevant to our main subject. The number of articles in this field follows an increasing trend, with more than 80% of publications published from 2018 onwards (Fig. 2). In the following subsections, we present and discuss the decision-making elements in FWV and their classification (Section 3.1), the DSA-FWV (Section 3.2), and the assessment indicators (Section 3.3); then we synthesize and propose the hourglass model for guiding future FWV decision-making (Section 3.4).

3.1. Decision-making elements and their classification

The key decision-making elements collected from the literature can be classified into three decision levels based on the research scope of the literature (Fig. 3; see also Table S1 for more details). The three decision levels include system-level, FWV option-level, and FW stream-level. Considering the commonalities of the research objectives, at each decision level, three types of research are generally involved to support FWV decision-making: (1) the understanding of the status quo, (2) the assessment of sustainability performance, and (3) the prioritization of the problem that needs to be addressed or the optimization of FWV practices. Based on the decision level and research type, various decision-making elements of FWV can be classified as shown in Fig. 3.

3.1.1. Decision-making at system-level

System-level decisions play a crucial role in addressing the status of the entire food system (Dora et al., 2021; Jurgilevich et al., 2016) as well as the socio-economical systems connected to the food system, e.g., regions (Ali et al., 2022; Lu et al., 2022) and industries (Amicarelli et al., 2021; Garcia-Garcia et al., 2019). These decisions encompass the overarching design, structure, and management of the system. To support decision-making at this level, it is essential to thoroughly understand the current status of the system, including its challenges, opportunities, policy, and market dynamics, and prevailing business models, all of which are important decision-making elements used by many previous studies (Ali et al., 2022; Bos-Brouwers et al., 2020; Cocchi, 2018; D'Adamo et al., 2020; Iacovidou and Voulvoulis, 2018; Kazancoglu et al., 2022; Metcalfe et al., 2017; Moggi and Dameri, 2021; Zheng and Ai, 2022) Understanding the current status of the system for FWV is typically achieved through qualitative literature reviews and interviews with relevant stakeholders. Some studies also quantitatively assessed the

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[1] (TS=(("food waste" OR "food loss" OR "food residues" OR "food side stream" OR "Food side flow" OR "vegetable waste" OR "fruit waste" OR "meat waste" OR "food by-product") AND ("valorization" OR "valorization" OR "circular*" OR "recovery" OR "recycling" OR "resource efficien*") AND ("framework" OR "model" OR "tool" OR "method*" OR "guidance" OR "infrastructure" OR "system" OR "route" OR "strateg*" OR "approach" OR "option*") AND ("assess*" OR "evalua*" OR "quantif*" OR "analys*" OR "estimat*" OR "calculat*" OR "measure*" OR "compar*") NOT ("kinetic*" OR "mathematic*" OR "behavi*" OR "solid waste" OR "Meta-analysis" OR "logistic*" OR "genetic*" OR ("condition*" AND ("improve*" OR "optimiz*"))))) *AND* **LANGUAGE**: (English) *AND* **DOCUMENT TYPES**: (Article) Indexes = SCI-EXPANDED, SSCI, A&HCI, ESCI Timespan = 2010–2021.

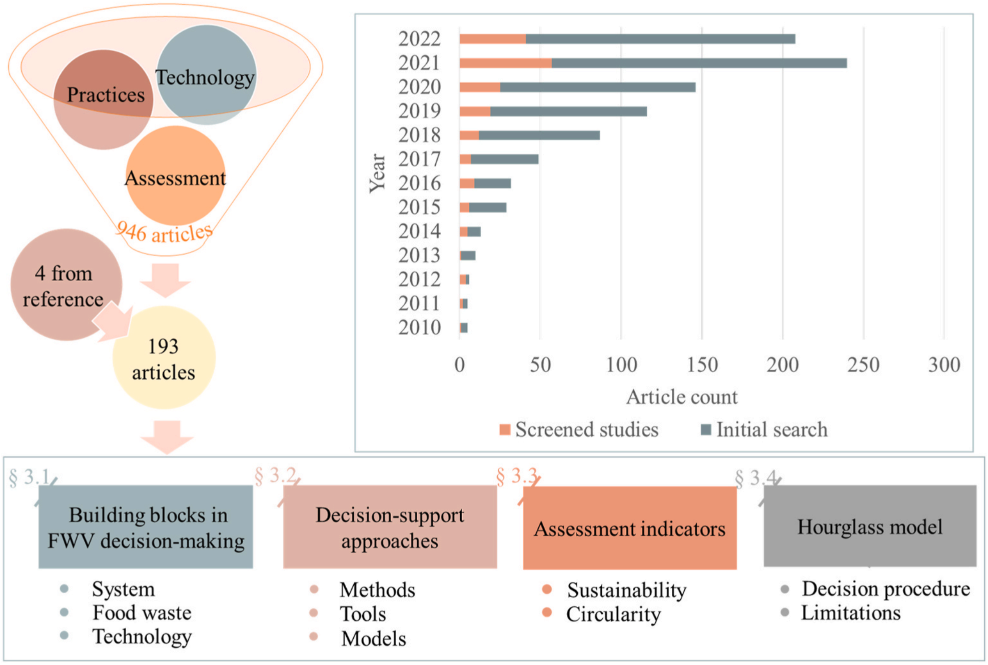

Fig. 2. The overall research approach of this study, including the literature acquisition process, the number of papers published in this research domain per year from 2010 to 2022, and the article structure. Initially, a comprehensive search yielded a total of 946 articles encompassing diverse topics, such as technology development and sustainability performance assessment. After the first screening, 189 articles were identified as relevant to the research goal, and an additional four articles were discovered through the references of these relevant studies. Notably, the number of articles exhibited exponential growth, as depicted in the bar chart. Ultimately, the study focused on 193 selected articles, and Section 3 presents and discusses the findings in four distinct sections.

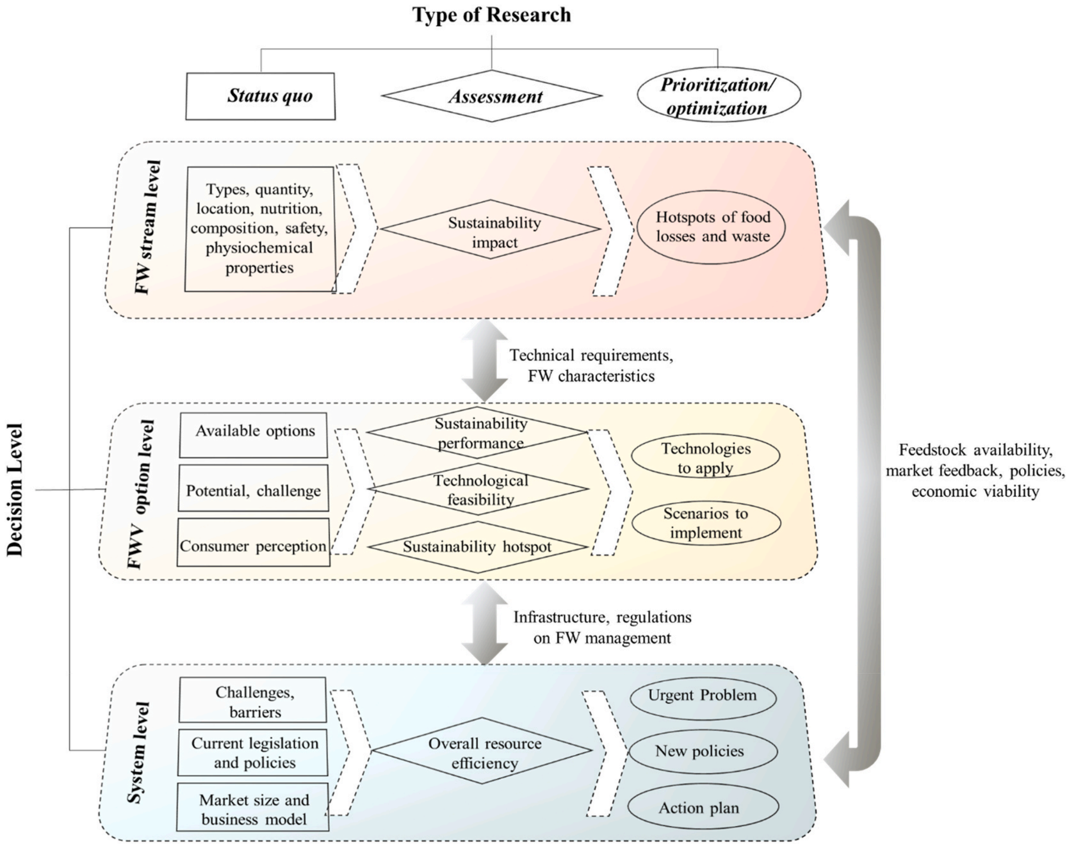

Fig. 3. Classification matrix of decision-making elements in food waste valorization decision-making. The three different colored boxes indicate the three decision levels, which are determined by the research scope of the literature (Table S1). The three shaped inner boxes indicate the three types of research at each decision level, which is determined by the commonalities of research objectives. The interplays between the different decision levels are indicated by gray double-headed arrows located between the decision-level boxes.

performance of the system. For example, Lu et al. (2022) employed the Data Envelopment Analysis to evaluate the circular efficiency of agricultural food production, consumption, and food waste recycling in the EU. Multi-criteria Decision Analysis (MCDA) is another method widely used to identify priority issues at system-level decision-making. Ali et al. (2022) identified and prioritized the barriers to changing FW management from a linear to circular pattern in Pakistan via MCDA. D'Adamo et al. (2020) incorporated MCDA into their newly proposed socio-economic indicator to identify the key actors and influential factors in the bio-based product value chain. All these system-level analyses not only provide policymakers with valuable insights and policy recommendations but also generate a holistic understanding of the system, thereby laying the foundation for decision-making at other levels.

3.1.2. *Decision-making at FWV option-level*

At the FWV option-level, usually, the potential FWV options for the focus stream are explored and selected. Most studies selected the potential FWV options based on two aspects: One is the technological suitability, which indicates the match between the technology (FWV options) and the raw material (FW streams); the other aspect is the sustainability performance of the valorization technologies. To identify suitable technologies for a certain FW stream, matchmaking between FW and valorization technologies should be undertaken considering FW characteristics and technology requirements. However, in most cases, researchers conducted unstructured literature reviews to inventory the valorization options for their FW streams (Brenes-Peralta et al., 2020; D'Adamo et al., 2020; Iacovidou and Voulvoulis, 2018; Manfredi and Cristobal, 2016; Mason and Burns, 2017; Stone et al., 2019). We notice that the matchmaking procedure has not received adequate attention in current studies, because the researchers tend to select the valorization technologies based on their own experience and knowledge, but this may lead to the neglect of some "suitable" or emerging technologies.

According to the literature study, the top five addressed valorization strategies are anaerobic digestion (AD) (43 times), animal feed (24 times), industrial uses (24 times), composting (22 times), and compound extraction (20 times) (see number of mentions in Fig. S1). This indicates that the high-tier options in the FW hierarchy are limitedly addressed compared with the mid-tier options (i.e., FW-to-nutrients, FW-to-energy, FW-to-animal feed, and FW-to-chemicals). On the other hand, the low-tier options which are located at the bottom of the FW hierarchy such as incineration and landfilling, were still often mentioned, namely 11 and 9 times, respectively. The high-tier options from the FW hierarchy, such as prevention, redistribution for human consumption, and conversion to human food via processing were mentioned only 2, 5, and 12 times, respectively. This means that in practice the mid-tier and low-tier options are much more reported and chosen than high-tier options. Two discussions could be extrapolated based on our understanding of the literature to explain why high-tier options in the FW hierarchy are overlooked.

The first plausible reason is that people have different understandings of "reuse." From Papargyropoulou et al. (2014) and Teigiserova et al. (2020), "reuse" refers only to the redistribution of food surplus and leaves out reprocessing, while Laso et al. (2018) define "FW-to-food" as the conversion of FW into human food by using it as feed. Re-manufacturing of FW directly into edible food or food ingredient (FW-to-food) is even missed in the existing FW hierarchies, which is a potential way to save FW and maintain the value of food material for a longer time (McHugh, 2019; van Boekel et al., 2010). There is an increasing number of emerging technologies that allow the reuse of FW as raw material to produce human food. An example is 3D printing for food manufacturing, where the compounds extracted from FW can be used as printing materials (Sun et al., 2015). Therefore we propose to add an extra tier of "conversion into human food by processing" in the FW hierarchy, as shown in Fig. 1. The new tier is located between "Redistribution for human consumption" and "Animal feed", and is categorized as "reuse." This will help avoid overlooking any potential valorization technologies, especially when the FW hierarchy is used as a theoretical guideline for FWV.

Secondly, the conversion of FW-to-food by default has strict requirements on feedstock, because of food safety traditions and regulations. This also limits the reuse of FW as raw material of human food. From the literature, feedstocks for FW-to-food applications only include side streams from the early stage of the food supply chain, such as the barley straw residue and lettuce waste from fresh-cut processing (Plazzotta et al., 2020; Stone et al., 2020). Huang et al. (2021) investigated the existing FWV cases in retail, and the result showed that only food surplus was used back to human food, while FW was only downcycled. Based on this, we speculate that only waste streams maintaining sufficiently high quality is currently considered to be reintroduced as ingredients in food processing. According to Davidek (2009), the quality of raw food materials includes hygienic-toxicological, nutritional, sensory, and technological aspects. Thus, depletion of nutrients and spoiling could be one of the reasons for the limited reuse of FW and by-products as raw materials in the food industry. The raw material of food manufacturing should at least meet safety requirements (Aung and Chang, 2014); however, the quality and safety of FW are difficult to track or predict in the current food supply chain, which may also hinder the implementation of FW-to-food (Aung and Chang, 2014).

It is also advised, though not yet extensively done in literature, to consider the future potential and practical challenges associated with each technology during the selection process, such as the scale-up potential and the regulatory challenges (Banu et al., 2021; Byun and Han, 2021; Hu et al., 2021).

Performance assessment of FWV technologies has emerged as a focal point in the existing literature, garnering extensive attention. We noticed that the assessment of environmental and economic performance is more prevalent compared to the assessment of social impact. However, the missing of social consideration can lead to a series of negative consequences. For example, certain valorization methods might conflict with local cultural values (Ali et al., 2022). Failure to understand the community acceptance of new valorization technologies may lead to social tension. Missing social consideration may also cause the overlook of opportunities for creating jobs or supporting local economies through valorization initiatives (Stone et al., 2020). The health implications of new valorization technology should also be considered to ensure the quality of human life will be positively affected by the new valorization technologies (Wenhao et al., 2016). In addition to the three pillars of sustainability, technical feasibility is increasingly incorporated in the studies. It is also advised, though not yet extensively done in literature, to consider the future potential and practical challenges associated with each technology during the selection process, such as the scale-up potential and the regulatory challenges (Banu et al., 2021; Byun and Han, 2021; Hu et al., 2021).

Section 3.2 provides a comprehensive overview of various approaches for performance assessments, while Section 3.3 outlines the indicators utilized in these assessments. Based on the review, two primary objectives of performance assessment can be highlighted. Firstly, it aims to facilitate comparison among different technologies and aid in the selection of solutions by identifying the best-performing options (Diaz et al., 2021; Kowalski et al., 2021; Siddiqui et al., 2021; Yoshikawa et al., 2021). Secondly, it contributes to enhancing valorization technologies by pinpointing the key contributors to the sustainability impact (Amato et al., 2021; Angili et al., 2022; Brancoli et al., 2021; Kowalski et al., 2021; Ncube et al., 2021; Nikkhah et al., 2021). Subsequently, the prioritization of valorization strategies or optimization of valorization scenarios is commonly achieved through the application of multi-criteria decision-making approaches, which are thoroughly explained in Section 3.2 (Plazzotta et al., 2020; Y. Wang et al., 2022).

3.1.3. *Decision-making at food waste stream-level*

FW stream-level decisions revolve around determining whether and to what extent one or multiple FW stream(s) should be utilized as a resource. The most common decision-making elements at this decision level, observed in the reviewed literature, are primarily about the status quo of FW, including types, quantity, location, and composition (Adelodun et al., 2021; Amicarelli et al., 2022; Bedoya-Perales and Dal' Magro, 2021; Brenes-Peralta et al., 2020; Bux and Amicarelli, 2022; Dong et al., 2022; Greggio et al., 2021; Ioannou et al., 2022; Jagtap et al., 2021; Lazic et al., 2022; Plazzotta et al., 2020; Silvennoinen et al., 2022; Stone et al., 2019). Typically, the information related to these decision-making elements at the FW stream-level is usually obtained through sampling with subjective estimation, mass flow analysis, and/or composition analysis (see Table S1). Considering the safety and nutritional aspects of reusing FW, particularly for upcycling FW resources, researchers highlight the importance of conducting nutritional analysis and safety assessments to ensure its suitability (Socas-Rodriguez et al., 2021; Tedesco et al., 2021). Furthermore, sustainability assessments, such as Life Cycle Assessment (LCA), Material Flow Cost Accounting, and other techno-economic analyses, are employed to evaluate the environmental and economic impact of current FW utilization (Amicarelli et al., 2022; Bux and Amicarelli, 2022; Plazzotta et al., 2020; Silvennoinen et al., 2022). Qualitative analysis and SWOT analysis are often employed to identify the opportunities and challenges and prioritize FW management strategies (Batista et al., 2021; Mason and Burns, 2017; Salmani et al., 2022; Stone et al., 2019). All the information obtained at the FW stream-level serves two purposes: first, help to identify the FW stream that requires immediate attention, and second, assist matchmaking between valorization technologies and FW streams (see Table S2 for further details on the FW characteristics that are important for technology selection).

3.1.4. Interplays between different decision levels

The interplay among these three levels is crucial in driving iterative improvements in the decision-making processes. There are three potential interplays, namely the interplay between system and FW stream, the interplay between FW stream and FWV options, and the interplay between system and FWV options. However, limited articles were found discussing the interplay between different decision-making levels. We found three articles about the interplay between the FWV option level and the system level, and only one article is about the interplay between the system level and the FW stream level. There is no literature specifically focusing on the interplay between FW streams and valorization options, but a few articles admit the importance of considering FW characteristics when selecting valorization options.

3.1.4.1. Between the FWV option-level and the system-level. The interplay between the FWV option and the system has been widely discussed in the literature, which determines how the system can better support the implementation of technologies and what benefits the system can obtain upon technology implementation. Some studies use methods such as Geographic Information Systems and LCA to evaluate the system features (e.g., feedstock availability, the capability of establishing feedstock supply chains, policies, and economic viability of specific technologies) (Jagtap et al., 2021; Kassem et al., 2022). A more dynamic and systemic approach for simulating and understanding this interplay is emerging in the literature; for example, Latka et al. (2022) used a global partial equilibrium model to evaluate the impact of reuse and reduction interventions on the market dynamics and the overall sustainability outcomes.

3.1.4.2. Between the system-level and the FW stream-level. The interplay between the system-level and the FW stream-level is characterized by how the FW stream status affects the system improvement and how the system can facilitate improved utilization of FW. A typical example of this interplay can be found in the study conducted by Salmani et al. (2022), wherein the waste oil status is explored using SWOT analysis. The outcomes derived from this analysis contribute to providing policymakers with suggestions for system improvement, including the implementation of local laws, regulations, and infrastructure for waste oil management. In turn, these system-level enhancements can facilitate better disposal and treatment of local waste oil. This example demonstrates the interaction and mutually beneficial influence between the system-level and the FW stream-level.

3.1.4.3. Between FW stream-level and FWV option-level. The interplay between FW stream and FWV options highlights how characteristics of FW can influence valorization technology selection and application, and simultaneously, the technical requirements of valorization options also influence the choice of FW stream as feedstock. This process is referred to as matchmaking, as discussed earlier. Patsios et al. (2016) claim that the physiochemical properties of the FW stream play a decisive role in determining the appropriate valorization route. Besides, Tedesco et al. (2021) emphasize the significance of considering safety when selecting suitable FW streams for animal feed production. Overall, the interplay among the three decision levels illustrates the interdependence of decisions at each level, serving as a link to all the decision-making elements in each level and potentially leading to an integral decision-making layout.

In addition to the research content mentioned above regarding the main decisions in FWV, there have been studies focusing on auxiliary facilities that play a key role in facilitating the transition toward a more sustainable food system. For instance, Brenes-Peralta et al. (2020) utilized Linear Programming to optimize the collection route of FW, while Ankathi et al. (2021) employed mixed-integer Linear Programming and geographic information to optimize the location, size, and number of the treatment plant. Other studies have also explored various aspects of facility choices, such as the selection of FW containers and transportation routes and options (Dolci et al., 2021; Zheng and Ai, 2022). Moreover, as we look beyond the current food system, emerging technologies like blockchain and big data-based analyses and optimizations are recognized as powerful tools for fostering sustainable development (Percin, 2022; Sharma et al., 2021). Before applying these emerging technologies in FWV decision-making, pre-evaluation is necessary to assess the suitability of applying them in FWV decision-making, highlighting their potential benefits and providing insights into their effective integration into the food system (Percin, 2022; Sharma et al., 2021).

3.2. Performance assessment approaches

To understand the assessment approaches applied in FWV decision-making, we conducted a comprehensive review encompassing their methodological specifications, focused decision levels, and the sustainability aspects they address. Overall, 22 prominent assessment approaches were identified and have been categorized into methods, models and tools, as elaborated in Table 1. The "method" denotes a well-established procedure designed to achieve specific assessment goals, such as quantifying the environmental benefits of FWV options. A "model" encompasses algorithms that enable the processing and analysis of data, enabling us to gain a deeper understanding and predict the behavior of the target system. A "tool" typically refers to a toolkit specifically developed to facilitate the execution of a particular task.

3.2.1. Method

Life Cycle Thinking is a widely adopted concept in sustainability performance assessment, encompassing various methods and approaches. Under this umbrella concept, LCA and Life Cycle Cost (LCC) are two prominent methods employed.

Among the 193 articles reviewed, 135 articles incorporated LCA in their research. In general, LCA is used to assess the environmental impact of valorization technologies and scenarios or to calculate the carbon footprint of an FW prevention action (e.g., redistribution of food surplus via foodbank), which is mostly at the FW stream-level and the at

Table 1
| Review of the performance assessment approaches in food waste valorization decision-making.

Category	Name	Methodological specifications						Decision level of the study	Performance assessment				Reference
		LCT	CBA	MBA	MCDA	LP	Other		env	eco	soc	tec	
Method	Life cycle assessment (LCA)	×						Str, Opt	×				Mondello et al. (2017)
	Dynamic LCA	×						Opt	×				Hu et al. (2021)
	Consequential LCA	×						Sys, Opt	×				Styles et al. (2015)
	Exergetic LCA	×		×				Opt	×				Vandermeersch et al. (2014)
	Emergy analysis & LCA	×						Sys, Str	×				Patrizi et al. (2020)
	PESTEL analysis	×						Sys, Opt	×	×	×	×	Iacovidou et al. (2017)
	Food-Energy-Water-Health nexus	×			×			Sys, Opt	×				Slorach et al. (2020a, b)
	Water-Energy-Food-Climate nexus	×				×		Sys, Opt	×				Laso et al. (2018)
	Life cycle cost (LCC)	×						Opt	×	×			Kim et al. (2011)
	Environmental LCC	×						Opt	×	×			Kim et al. (2011)
	Societal LCC	×						Opt, Sys	×	×	×		Albizzati et al. (2021)
	Mass and Energy Balance	×		×				Opt				×	Banu et al. (2021)
	Input-output analysis (IOA)						IOA	Opt		×		×	Yoshikawa et al. (2021)
	Material flow analysis			×				Str	×	×			Amicarelli et al. (2021)
	Substance flow analysis			×				Str, Opt, Sys	×				Cooper and Carliell-Marquet (2013)
	Cost Benefit Analysis		×					Opt		×			Satayavibul and Ratanatamskul (2021)
	Gross profit analysis						Profitability analysis	Opt		×			Yang-Jie et al. (2023)
	Techno-economic analysis		×	×				Opt		×		×	Kwan et al. (2018)
	Pre-feasibility analysis and waste reduction algorithm		×	×			Straight Line Depreciation	Opt	×	×		×	Ortiz-Sanchez et al. (2020)
	Environmental balance						Environmental balance	Opt	×				Panepinto et al. (2015)
	Feasibility analysis	×	×				Acceptability and scalability analysis	Sys, Opt	×	×	×	×	Joensuu et al. (2022)
Model/ Tool	LCA-EASEWASTE	×						Opt	×				Zhao and Deng (2014)
	M^3-IS-LCA	×						Sys, Str	×				Kerdlap et al. (2020)
	Waste Flow Modelling methodology			×				Sys, Str, Opt	×	×		×	Garcia-Garcia et al. (2019)
	FW cost-benefit analysis tool		×					Sys, Str, Opt		×			WRAP (2020)
	FORKLIFT (REFRESH)	×						Opt	×	×			Östergren (2019)
	DIRECT						Cost analysis	Opt		×			Verghese et al. (2018)

Abbreviations.
Methodological specifications:LCT: life cycle thinking, MCDA: multi-criteria decision analysis, MBA: mass balance approach, CBA: cost-benefit analysis, LP: linear programming.
Decision level of the study: Sys: System-level, Str: FW stream-level, Opt: FWV option-level.
Performance assessment:env: environmental, eco: economic, soc: societal, tec: technological.
Methods: PESTEL analysis: political, economic, social, technological, environmental, and legal analysis; EASEWASTE: Environmental Assessment of Solid Waste Systems and Technologies, M^3-IS-LCA: a methodology for multi-level life cycle environmental performance evaluation of industrial symbiosis networks, FORKLIFT: food side flow recovery life cycle tool, DIRECT: dynamic industry resource efficiency calculation too.

FWV option-level. Some studies simply use conventional LCA with different impact assessment methods such as CML2 Baseline2000 (Mondello et al., 2017), ReCiPe (Mosna et al., 2021; IPCC, 2013; IPCC, 2013), which complicates the comparisons across studies. Some use more innovative LCAs; for example, Hu et al. (2021) utilized dynamic LCA to assess the environmental benefits of scaling up lab-scale production to pilot plant production. Iacovidou et al. (2017) developed the multi-aspect Life Cycle Sustainability Assessment, which integrates Political, Economic, Social, Technological, Environmental, and Legal considerations. Additionally, some studies devised their nexus approaches based on the Food-Energy-Water nexus; for example, Slorach et al. (2020a,b) incorporated human health into the nexus, while Laso et al. (2018) integrated climate change into the nexus. Furthermore, LCA is often combined with other methodologies to enhance its assessment capabilities; for instance, Patrizi et al. (2020) and Vandermeersch et al. (2014) employed LCA in conjunction with emergy analysis and exergy analysis, respectively. The diverse range of LCA approaches utilized in DSA-FWV studies enables the evaluation of multiple performance aspects beyond the environmental perspective. However, this diversity also hinders the comparison and benchmarking across different studies.

LCC and cost-benefit analysis are the main economic assessment approaches employed in evaluating FWV scenarios. Some studies also assess profitability using other techniques such as gross profit analysis and input-output analysis (Yang-Jie et al., 2023; Yoshikawa et al., 2021). However, most of these methods tend to focus on the costs and benefits associated with the foreground system while overlooking the background system. There are some attempts to address this limitation. For example, Kim et al. (2011) defined the system boundary in their LCC analysis, encompassing discharge, collection, transportation, treatment, and final disposal. Verghese et al. (2018) introduced the concept of the “true cost of the waste” to further comprehend these methods, which includes the costs along the whole life cycle of the material, such as the cost of raw material, labor, disposal, production loss, and finished product loss. However, these studies still take a microeconomic perspective and do not explore the macroeconomic influence of FWV. Recently, Latka et al. (2022) developed a global partial equilibrium model called the Common Agricultural Policy Regionalized Impact Modelling System as an example to address the macroeconomic perspective of FWV. This model evaluates the impact of specific FW treatment strategies on the entire agriculture system, providing not only policy suggestions but also insights into the economic effects, such as food prices and farmers' income. While LCC and other economic assessment methods have been widely employed, there remains a need for further attention to the macroeconomic perspective of FWV. The study by Latka et al. (2022) provides promising opportunities to evaluate the broader economic impact of FWV strategies on various sectors, supporting decisions not only at the FWV option-level but also at the system-level.

The technological performance is commonly assessed to support decision-making at the FWV option-level, encompassing two key aspects: production efficiency and technological feasibility. Production efficiency evaluates the effective utilization of resources in achieving desired outputs, considering factors such as waste minimization, cost reduction, resource optimization, and maximizing output relative to available resources (Amicarelli et al., 2021; Banu et al., 2021; Cooper and Carliell-Marquet, 2013; Kwan et al., 2018). The mass balance approach is commonly employed to assess FWV production efficiency. Studies addressing technological feasibility, on the other hand, determine whether an FWV technology or solution can be efficiently implemented and operated within the relevant technical constraints and requirements. For instance, Joensuu et al. (2022) discuss the acceptability and scalability of proposed FWV options, focusing on feedstock supply and processing capacities for scalability. Hu et al. (2021) conducted scale-up simulations and assessed the sustainability performance of the technology at an industrial scale, which helps to determine the suitability of the technology when scaled up. Byun and Han (2021) demonstrated the energy recovery and conversion of FW as part of their evaluation of the benefits associated with scale-up. Although production efficiency has received extensive attention and discussion in the literature, scalability remains underexplored. Further research is necessary to develop a comprehensive approach for evaluating scalability in FWV.

Many studies recognize the need to evaluate multiple dimensions of sustainability performance and employ techniques such as Multicriteria Decision Analysis and Linear Programming to address the trade-offs involved. For instance, in the context of the Food-Energy-Water-Health nexus, Slorach et al. (2020a,b) utilized Multicriteria Decision Analysis to estimate the overall environmental impact, while Laso et al. (2018) employed Linear Programming to determine the optimal aggregation of weighting factors, leading to an aggregated nexus index known as the Water-Energy-Food-Climate Nexus Index. Other popular Multicriteria Decision Analysis methods like PROMETHEE, AHP (Analytic Hierarchy Process), and TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) have also been utilized in FWV studies to rank different valorization options (Al-Aomar et al., 2022; Erceg and Margeta, 2019; Patel et al., 2021). Additionally, data envelopment analysis has been adopted since 2016 in waste management decision-making to identify efficient and inefficient options (Cristóbal et al., 2016; Lu et al., 2022; Payandeh et al., 2021).

3.2.2. Models and tools

The models and tools developed in the reviewed studies usually serve specific objectives, aiding decision-makers in gaining a systematic understanding of complex systems and facilitating the quantification and evaluation of multiple performance aspects. These models encompass a range of methods and algorithms that facilitate data processing and deliver the desired outcomes. For example, Zhao and Deng (2014) employed the LCA modeling software, named EASEWASTE, to assess the environmental impacts of FW management and the effects of the energy mix. Kerdlap et al. (2020) introduced M^3-IS-LCA, a multi-level matrix-based modeling approach, for analyzing the life cycle environmental impacts of industrial symbiosis networks. Garcia-Garcia et al. (2019) utilized Waste Flow Modelling to comprehend current food manufacturing activities and evaluate existing FW management practices, thereby establishing a basis for implementing alternative FWV solutions.

In addition to models, several user-friendly decision-support tools have been developed to streamline the evaluation process. This review includes three such tools: the FW cost-benefit analysis tool, *FORKLIFT*, and *DIRECT*. The FW cost-benefit analysis tool, developed by the FW reduction action program WRAP, aids in assessing the costs and associated benefits of implementing proven intervention measures (WRAP, 2020). FOKLIFT, created under the EU program REFRESH, provides stakeholders with a general understanding of valorization options, highlighting their environmental impacts and costs (Östergren, 2019). DIRECT, introduced by Verghese et al. (2018), serves as a tool for engaging stakeholders from various industries, particularly food manufacturers, to promote improved resource management and achieve better sustainability outcomes. Overall, the models and tools are normally applied to support multi-level decisions, especially for the decisions at the FW stream-level and FWV option-level.

3.3. Indicators in assessment

To understand what indicators are relevant to FWV, we reviewed the indicators commonly used in the literature. Overall, two categories of indicators are identified, one is for sustainability assessment, and the other one is for circularity assessment. Within the scope of sustainability assessment, the indicators are divided into four subgroups based on which performance they are measuring, i.e., environmental impact, economic impact, societal impact, and technological feasibility.

3.3.1. Indicators for sustainability assessment

Table 2 summarizes the criteria and indicators related to sustainability performance and technology feasibility. Environmental and economic indicators have been extensively studied and applied in FWV research, and they are normally assessed using quantitative procedures. Most of the environmental indicators are from LCA and measure single-dimension performance, such as Global Warming Potential, Cumulative Energy Demand, Bluewater Consumption, and Human Toxicity (Erceg and Margeta, 2019; Monteiro et al., 2020; Usubiaga et al., 2018; Wenhao et al., 2016). There are also multi-dimension indicators, which measure the multiple environmental impacts, such as Energy, Water, and Mineral Efficiency (Stone et al., 2019) and the Water-Energy-Food-Climate nexus (Laso et al., 2018). The indicators for FWV economic performance, such as Net Present Value, Pay-Back Time, and Return on Investment, are typically measured by cost-benefit analysis (Kwan et al., 2018; Plazzotta et al., 2020; Stone et al., 2020). It should be noted that some of the indicators measure similar attributes. For instance, both "Energy, water, and mineral efficiency" and "Ecological footprint" measure resource consumption, and both "Economic potential" and "Annual Net Profit" estimate the profit of the business. Technological feasibility is another emerging assessment aspect in recent years. In FWV decision-making, technological feasibility refers to the maturity and suitability of the technology. For instance, Stone et al. (2020) employed Technology Readiness Level, Integration Readiness Level, and Demand Readiness Level, which assess the technology's maturity, compatibility with existing technologies, and market demand, respectively. Moreover, it is also important to include safety and risk analysis in the technological feasibility analysis, considering that food by-products and wastes may contain chemical contaminants or potential pathogens that pose risks to consumer health (Socas-Rodriguez et al., 2021). In general, technological feasibility indicates the readiness, scalability, compatibility, performance, and safety aspects of technology.

The social performance indicators did not receive sufficient

Table 2
The indicators measuring the environmental, economic, societal sustainability, and technological feasibility.

Type of criteria	Indicators	Data needed for calculations	Unit	Reference
Environmental	Global warming potential (GWP) or Climate Change Potential (CCP)	Mass, compositions, stream value	kg CO_2-eq	(Erceg and Margeta, 2019; Stone et al., 2020)
	Land Occupation or Land Use Change (LUC)	Land use area	m^2 -years	Styles et al. (2015)
	Bluewater consumption	Groundwater, river water	m^3	Usubiaga et al. (2018)
	Energy, water, and mineral efficiency (EWME)	Energy, water, mineral consumption, production	volume consumed/ton product	Stone et al. (2019)
	Cumulative exergy losses (CEL)	Mass, exergy	MJ/kg	Zisopoulos et al. (2015)
	Cumulative energy demand (CED)	Direct and indirect energy use along the product life cycle	MJ/g final product	Monteiro et al. (2020)
	Primary energy saving (PES)	Bioenergy obtained from food waste; standard coefficient (natural gas conversion into tons of oil equivalent)	ton/year	Plazzotta et al. (2020)
	Ecological footprint	Mass of resources, global resource productivity area	Gha (global hectares)	(L. Wang et al., 2018)
	Human Toxicity Potential (HTP)	Characterization factors of the toxic substances; factors (person equivalent)	CTUh/mPE year Or CTUh/kg	Stone et al. (2020)
	Ecotoxicity potential	Characterization factors of the toxic substances; factors (person equivalent)	CTUe/mPE year	
	Human toxicity (non-carcinogens/carcinogens	Mass of non-carcinogens/carcinogens; factors	kg C2H3Cl-eq/kg 1.4-DB -eq	Wenhao et al. (2016)
	Freshwater-toxicity potential (ETP)	Mass of toxicities in freshwater	kg TEG-eq	
	Marine water eco-toxicity potential (ETP)	Mass of toxicities in marine water	kg TEG-eq	
	Terrestrial eco-toxicity potential (ETP)	Mass of toxicities on land	kg TEG-eq	
	Ozone Depletion Potential (ODP)	Mass of nitrogen oxides; mass of volatile organic compounds; factors	kg CFC-11-eq/mPE year	Wenhao et al. (2016)
	Photochemical oxidation potential (POCP)	Mass of volatile organic compounds	m^2 *ppm*hours or kgC_2H_4-eq	
	Photochemical Ozone Formation Potential (POFP)	Mass of nitrogen oxides; the mass of volatile organic compounds; factors (1 kg carbon monoxide = 0.046 kg NMVOC eq.; 1 kg nitrogen oxides = 1 kg NMVOC eq.)	kg NMVOC eq.	Stone et al. (2020)
	Aquatic and Terrestrial Eutrophication Potential (EP)	Emission of species (e.g., NO_x, $NH_4{}^+$, N, PO_4^{3-}, P), and their respective eutrophication potentials	kg $PO_4{}^{3-}$ -eq or kg NO_3-eq or m^2 UES or kg N eq./mPE year	Mondello et al. (2017)
	Acidification Potential (AP)	Acidification potential of a specific gas (expressed relative to the AP of SO_2), emission in kg per functional unit	Kg SO_2-eq or m^2 UES or AE/ mPE year	Stone et al. (2020)
	Environmental load	Analysis based on the literature	A scale of 1–6	Erceg and Margeta (2019)
	Visual and landscape impact	Analysis based on the literature	A scale of 1–6	
	Resource efficiency	Expert judgment	Normalized scale	D'Adamo et al. (2020)
	Water-Climate-Food nexus index	Amount of FLW, primary energy consumption, water consumption	No unit	Hoehn et al. (2021)
	Food-Energy-Water-Health nexus	Food: agricultural land occupation, urban land occupation, natural land transformation, terrestrial ecotoxicity, terrestrial acidification, and GWP. Energy: primary energy demand, metal depletion. Water: water depletion, freshwater/marine eutrophication, freshwater/marine ecotoxicity. Health: human toxicity, particulate matter formation, photochemical oxidant formation, ozone depletion	No unit	Slorach et al. (2020)
	Water-Energy-Food-Climate nexus	Water and energy consumption, GWP, and food obtained from FW management	No unit	Laso et al. (2018)
Economic	Net present value (NPV)	Cash flow; discount rate	€	Stone et al. (2020)
	Economic potential	Product sales/year; raw material cost/year	Σ (product sales/year) − raw material costs/year	Kiskini et al. (2016)
	Profit/Sales Revenue (SR)	Sales; average price	€	Iacovidou and Voulvoulis (2018)
	Annual net profit	Revenues; "White Certificate" incentives; operation and maintenance cost	€	Plazzotta et al. (2020)
	Pay-back time (PB)	Total investment cost; annual net profit	years	
	Costs (for a municipality and/or company)	Cost of raw material, capital, operational & maintenance; utilities (e.g., energy, water); waste treatment; collection and transport; illnesses and accidents	€	(D'Adamo et al., 2020; Erceg and Margeta, 2019)
	Government Subsidies/ Incentives (GSI)	Policy	€/unit of capacity	Stone et al. (2019)
Social	Social Acceptability	Survey	+/++	Stone et al. (2020)
	Odor Generation	Survey	+/++	
	Noise Creation	Survey	dB	
	Job Creation (JC)	Mass of FW, number of job creation	Number of people benefitted/ton	
	Traffic Generation	Mass of FW, number of vehicles	Number of vehicles/ton FW	
	The cumulative risk of fair wage in the supply chain	Survey, wage	Semiquantitative results	Wenhao et al. (2016)

(*continued on next page*)

Table 2 (*continued*)

Type of criteria	Indicators	Data needed for calculations	Unit	Reference
	Cumulative fatality rate (injury rate) in the supply chain	Survey	Number of cases	
	Cumulative working time in the supply chain	Total working time	Second (s)	
	Avoided environmental costs on human health in the supply chain	Environmental cost	Euro $_{2003}$	
	Green job per euro invested	Number of Green jobs created and investment	Number of green jobs per euro invested	Erceg and Margeta (2019)
	Tech innovation in treatment over time	Analysis based on the literature	A scale of 1–6	
	Labor intensity	Analysis based on the literature	A scale of 1–6	
	The accident rate in the workplace	Analysis based on the literature	Number of accidents per year	
	Occupational risks	Analysis based on the literature	A scale of 1–6	
	Time/space for home waste	Analysis based on literature/survey	A scale of 1–6	
	Percentage of the workforce hired locally	Analysis based on the literature	Percentage	
	Worker welfare	Expert judgment	Normalized scale	D'Adamo et al. (2020)
	Social investment	Expert judgment	Normalized scale	
	End-of-Life Responsibility	Expert judgment	Normalized scale	
	Transparency	Expert judgment	Normalized scale	
	Brand Fit	Survey	Linkert Scale (1–5)	
	Expertise Fit	Survey	Linkert Scale (1–5)	
	New value chain	Expert judgment	Normalized scale	D'Adamo et al. (2020)
	Access to material resources	Expert judgment	Normalized scale	
Technological feasibility	Technological Maturity	Technology Readiness Level (TRL) ranking Integration Readiness Level (IRL) ranking Demand Readiness Level (DRL) ranking	A scale of 1–9 A scale of 1–7 A scale of 1–9	Stone et al. (2020)
	Technological efficiency	Analysis based on the literature	A scale of 1–6	Erceg and Margeta (2019)
	Efficiency, safety, reliability, maturity	Analysis based on the literature	A scale of 1–6	
	Microbiological hazards	Presence of pathogenic microbes, antibiotic-resistant bacteria	CFU/mL or CFU/g	Furukawa et al. (2018)
	Physicochemical and quality	Moisture, acidity, ash content, color determination, nutritional value, texture profile, water-holding capacity, or oil-holding capacity	Depends on the characteristics	Socas-Rodriguez et al. (2021)

discussion in the literature compared to the indicators measuring other perspectives. This overlook may be attributed to two key reasons. Firstly, the primary focus of academic research in this field has centered on the environmental aspects and techno-economic feasibility of valorization technologies, while governments and practitioners pay more attention to social considerations. In practice, extensive stakeholder consultation and public perceptions are often involved in decision-making when planning for new food waste valorization facilities (Morone and Imbert, 2020). This is also a limitation of literature review: The criteria and indicators come only from academic literature and there are more examples used by practitioners. Secondly, social indicators are more difficult to define, measure, and quantify compared to indicators of other sustainability aspects. Many social indicators rely on stakeholder and expert evaluations through interviews or surveys (Brenes-Peralta et al., 2020; D'Adamo et al., 2020; Stone et al., 2020; Wenhao et al., 2016). The subjective and context-specific nature of these indicators and evaluations makes their integration into non-case-study-based studies more complex. However, social sustainability deserves attention, especially when a new technology or system is introduced. To promote responsible practices and increase the possibilities of long-term success, future study is needed to better define and measure social sustainability performance, foster the engagement of all parties, and facilitate the implementation of FWV initiatives.

Table 3
The indicators measuring circularity of the food waste resources.

Circularity indicators	Measure	Type of data needed	Unit	Applied to FLW	Reference
Energy sustainability index (ESI)	Ratio of energy produced to energy consumed	The energy produced and consumed	% (MJ/MJ)	Yes	Malave et al. (2018)
Eco-efficiency	Ratio of quantity of sold product to quantity of raw materials used to produce them	Mass	% (kg/kg)	Yes	Garcia-Garcia et al. (2019)
Eco-intensity	Ratio of quantity of raw materials used to produce a product to quantity of product sold	Mass	% (kg/kg)	Yes	
Rate food waste/product	Ratio of quantity of food waste generated to quantity of product sold	Mass	% (kg/kg)	Yes	
Rate food waste/raw materials	Ratio of quantity of food waste generated to quantity of raw materials used	Mass	% (kg/kg)	Yes	
Bioresource utilization index	The efficiency of bioresource use in an enterprise, along with the enterprise's contribution to the bioeconomy	Mass	0-1 Index	Yes	Vamza et al. (2021)
Material Circularity Indicator (MCI)	Material recirculation degree	Mass	0-1 Index	Not yet	Goddin et al. (2019)
Circularity index (CI)	The product of quality circularity degree and quantity circularity degree (quality circularity degree = energy required for material recovery/energy required for primary production)	Energy consumed, mass	≤ 1 index	Not yet	Cullen (2017)

3.3.2. Indicators for circularity assessment

The circularity indicators refer to the indicators focusing on technological cycles and calculating the degree of circularity (on a scale of 0–10 or 0–100%), in other words, excluding cause-and-effect modeling aspects of Life Cycle Thinking. They normally use mass and energy consumption as input data and adopt the mass balance approach to evaluate the circularity. Table 3 lists the indicators assessing circularity, including six indicators previously employed in FWV studies, as well as two indicators derived from circular economy research that have yet to be integrated but may be extended and applicable to FWV. Material Circularity Indicator (MCI) was originally designed for technical cycles and non-renewable materials in 2015 and was extended to include the treatment of biological materials in 2019 (Goddin et al., 2019). Following this, Rocchi et al. (2021) modified and applied MCI to the poultry industry. Circularity index (CI) measures the circularity from both quantitative and qualitative aspects (Cullen, 2017). The quality of materials is quantified as the ratio of energy required for material recovery to energy required for primary production. CI is seemed applicable for measuring FWV because valorizing FW can be energy-intensive (e.g. pretreatment of FW) and may consume more energy than producing from the virgin feedstock. Thus, CI can help better understand the circularity performance of FWV from an energy point of view.

3.4. The hourglass model for FWV decision-making

Having all the decision-making elements and DSA-FWV, we further investigated the scope and process of the decision-making in each study. In combination with the knowledge from Fig. 3, four decision-making components are found repetitively occur in the reviewed articles: (1) the context information such as the status quo of the food system or FW streams; (2) the problem related to FW management (including prevention and valorization) or the hotspot of FW that need to be addressed; (3) the opportunities to solve the problems such as the possible FW reduction practices or valorization options; (4) the action plan developed based on the prioritized opportunities, such as an optimized FWV scenario. These four components are summarized as *context information*, *problem identification*, *possible solutions*, and *action plans*, and these individual components can be interconnected through "assessment" to form an hourglass-shaped model, as illustrated in Fig. 4. The relationship between decision elements and decision levels is also shown in Fig. 4. Combined with Table 1, the appropriate performance assessment approaches can be identified.

It should be noted that any of the four components can be the starting point of the decision-making process, which aligns with the reversibility of the hourglass. For example, Salmani et al. (2022) investigated the problems in edible waste oil stream management first, while Amato et al. (2021) started with the evaluation of potential valorization options. To validate this synthesized decision-making model, namely the hourglass model, we further checked the established decision science principles. The result shows that the components and their arrangement in the hourglass model are consistent with the conventional decision-making process (Lunenburg, 2010).

While studies may focus on different components of the decision system, these components have not received equal attention in existing studies. Most of the studies are found primarily focused on assessing possible solutions for identified problems and feedback between

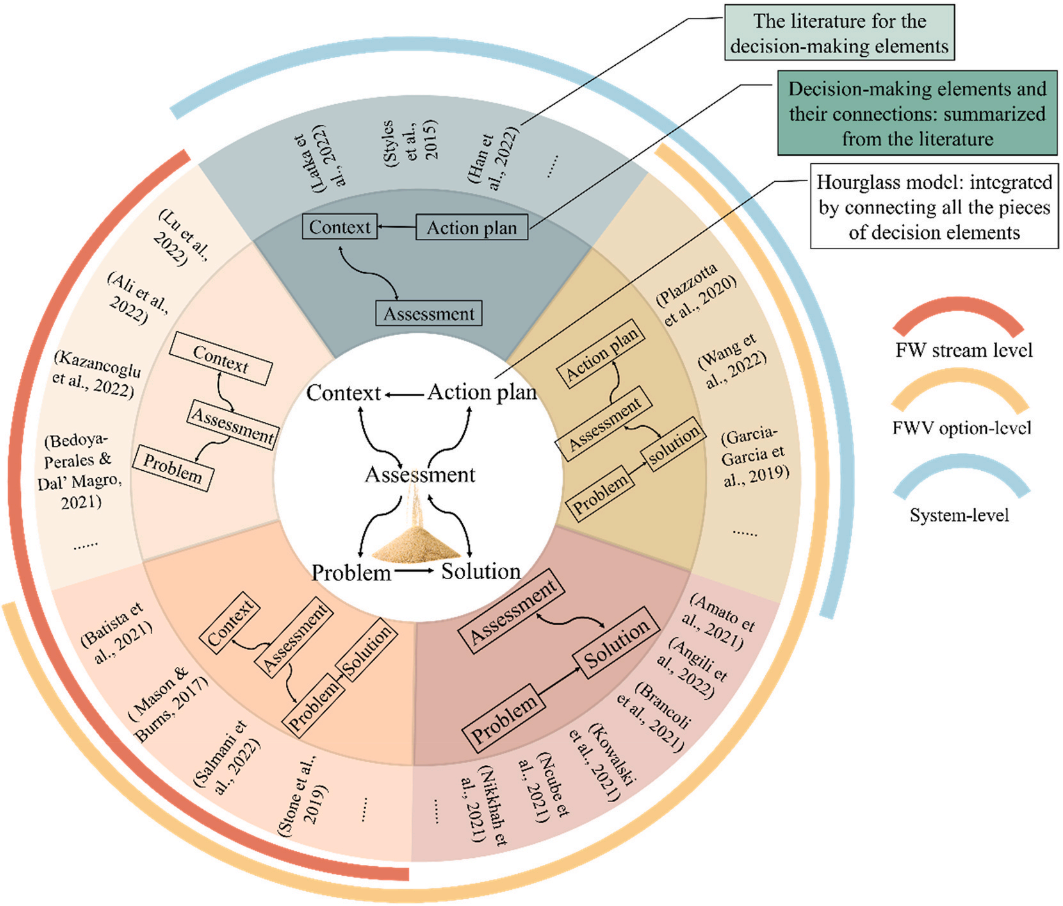

Fig. 4. The formation of the hourglass model. The hourglass model (in the center) demonstrates the decision-making layout for the practice of Food Waste Valorization. The outer circle lists the literature from which the decision-making elements were derived, and the middle circle shows the connections between these decision-making elements. The arcs indicate the relationship between the decision-making elements and the three decision levels.

solution and assessment. In the assessment step, the assessment approach and indicators should be picked based on the research objective carefully. A typical type of study in FWV decision-making is assessing valorization technologies, such as the research conducted by Amato et al. (2021) and Angili et al. (2022). Following the evaluation, some studies also further developed implementation plans or optimized scenarios for implementation, such as the work by Garcia-Garcia et al. (2019) and Plazzotta et al. (2020). In recent years, there has been an increasing focus on problem identification. Some researchers assess the status quo of the food system to identify promising areas for FW reduction or the need for primary governance, as seen in studies by Bedoya-Perales and Dal' Magro (2021) and Lu et al. (2022). Others analyze challenges within the current food system, such as the research conducted by Kazancoglu et al. (2022). Additionally, some studies address opportunity identification following context assessment and problem identification. For instance, Batista et al. (2021) provide a future scenario for advancing FW management after assessing the status quo. However, only a few articles focus on the planning of implementing new action plans and the systematic analysis at the system-level. For example, Han et al. (2022) conducted a plant-scale process modeling, designed conversion pathways for FW, and analyzed the environmental benefits from a global perspective. The reason for the shortage of literature on this topic could be the lack of interest in academics to do such research as we discussed before. The practitioners have more experience in this, and then, a convenient and efficient way for the practitioners to share their experience and knowledge becomes an important topic.

In addition, two double-headed arrows signify the feedback relationship within the proposed hourglass model. One arrow connects context and assessment, indicating that the assessment can provide valuable feedback to enhance the system. For example, Salmani et al. (2022) examined the status of edible oil waste using SWOT analysis and recommended that policymakers utilize their findings to establish laws and regulations for the safe disposal and reuse of edible oil waste. The other double-headed arrow links solution and assessment, implying that the assessment can provide feedback to improve the potential solutions, such as valorization technologies. This is exemplified in studies conducted by Amato et al. (2021) and Brancoli et al. (2021), where the assessment findings inform enhancements in valorization technologies.

The hourglass model is the first attempt to integrate all the studies in this field and aims to pave the way for a more standardized decision-making protocol, to overcome the barriers hindering progress in this research area, such as diverse system boundaries and DSA-FWV as mentioned in the introduction. A standard model can aid the utilization of knowledge and research findings, foster benchmarking and comparison among various studies, and enable the integration of results to yield comprehensive information. Moreover, it empowers stakeholders by providing a holistic understanding of different decision stages and their placement within the larger context. Under the hourglass model, the overlooked sustainability perspective can also be incorporated by pinpointing the relevant decision-making elements. For example, social indicators, which are overlooked in the current studies, can be emphasized by 1) paying more attention to societal considerations in the step of “action plan” and “context”, 2) developing and incorporating more social indicators in the step of “assessment”. This enhanced awareness may facilitate communication, collaboration, and stakeholder engagement during the transition of the food system. We envision that by utilizing this model, researchers can better formulate their research narratives and effectively position their studies within the entire FWV decision-making system. Similarly, decision-makers can determine their decision-making starting point by checking their available resources and information within this model. To sum up, the hourglass model aims to contribute to the standardization of decision-making in FWV, and highlights the necessity of understanding the holistic sustainability of the entire food system, thus underscoring the importance of collaborative studies involving various disciplines and stakeholders.

4. Conclusion and outlook

The main objective of this study is to provide a comprehensive understanding of the decision-making process and decision-support approaches within the field of FWV, while also constructing the decision-making layout to guide the decision-making, as food waste hierarchy was found not always guide decisions towards sustainability, especially from an environmental perspective. Through this literature review, we analyzed all the decisions addressed and classified them based on their commonalities. The findings reveal that decision-making occurs at three distinct levels: the system-level, the FW stream-level, and the FWV options level. To facilitate decision-making, three types of research are typically involved, encompassing the understanding of the state quo of affairs, the performance assessment of the system, waste streams, or valorization technologies, and the prioritization of problems to be solved or optimization of problem-solving approaches. Notably, decision-support approaches have been well-developed for assessing environmental and economic performance, as well as technological feasibility, with a wide range of indicators available for these assessments. Besides the indicators for traditional sustainability pillars, the circularity of resources also contributes to understanding the sustainability performance of the FWV. Selecting the appropriate assessment approach and indicators is contingent upon the specific case and the existing knowledge of decision-makers. In the end, the hourglass model maps the decision layout of FWV, representing the first attempt to integrate and connect various studies in this field. The goal of this model is to promote the standardization of decision-making in FWV and overcome the barriers arising from the diverse decision-making processes and methods. The hourglass model also helps to address the issues of food waste hierarchy from two perspectives. First, the food waste hierarchy has a limited scope and only provides various valorization options, but other critical decision elements are missing. The hourglass model could help researchers and decision-makers expand and identify the right scope of their research. Second, the prioritization of the valorization options may be wrong in some cases. The hourglass model emphasizes picking appropriate options via holistic assessment instead of following an established order. Following the hourglass model will help decision-makers think beyond the food waste hierarchy and therefore holistically consider the sustainability impacts of FWV.

Some limitations of existing studies are also observed. Firstly, there is still a research gap on efficient matchmaking between FW and valorization technology, although some studies highlighted the FW characteristics in selecting valorization technologies. Secondly, current economic assessment methods fail to adequately address the macroeconomic impact of FW (and FWV). Considering the potential changes and impacts on various sectors as FWV initiatives are implemented, a macroeconomic viewpoint becomes crucial. Thirdly, societal sustainability is overlooked, requiring increased awareness and robust methodologies and indicators to capture the social impacts of FWV. To enable a more comprehensive and inclusive approach to FWV practices, embracing collaboration among interdisciplinary teams, including social scientists, industrial representatives, consumers, and policymakers, becomes crucial.

By synthesizing and analyzing existing studies, this literature review offers a holistic sustainability-driven decision-making process for FWV practices. With this study, we aim to not only shape the direction of future research but also encourage meaningful yet overlooked interdisciplinary collaboration. Ultimately, we seek to accelerate the transition towards circular and resource-efficient food systems, aligning with the UN sustainable development goals, particularly goal 12: Ensure sustainable consumption and production patterns.

CRediT authorship contribution statement

Yujun Wei: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marta Rodriguez-

Illera: Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Xuezhen Guo:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **Martijntje Vollebregt:** Writing – review & editing, Project administration, Formal analysis, Conceptualization. **Xuexian Li:** Writing – review & editing. **Huub H.M. Rijnaarts:** Writing – review & editing, Formal analysis. **Wei-Shan Chen:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT (3.5) to check the grammar and readability of the selected sentences. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

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

Data availability

I have shared all the data in the manuscript and the supplementary material.

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Appendix A. Supplementary data

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