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Ontologies relevant for improving data interoperability for food loss and waste: A review and research agenda

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ABSTRACT

Food loss and waste (FLW) is a global challenge. Interoperable FLW ontologies will foster more comprehensive data sharing and inform better solutions to reduce and recover excess food and to valorize wasted food and food byproducts. This review reveals that only eight ontologies currently address FLW with most emphasizing valorization. Notably, few are designed explicitly to support FLW reduction, and none facilitate food recovery, which is critical given that reduction and recovery are the preferred means of mitigating FLW. Furthermore, existing FLW ontologies show limited alignment with recognized gold-standard frameworks, for example the Open Biological and Biomedical Ontology (OBO) Foundry, and none support ongoing connectivity to external ontologies, restricting their utility across stakeholder domains. Looking ahead, there is a pressing need to create or expand ontologies that adhere to best practices from relevant foundries to ensure robust linkage and interoperability and undergird structured data ecosystems that support food systems stakeholders in FLW prevention and mitigation. Achieving this goal will require active collaboration among a diverse range of stakeholders, including builders of food systems cyberinfrastructure, scientists, innovators, regulators, public and private funders, community-based organizations, policymakers, and international NGOs as each rely on critical ontological elements to inform decision-making, measure impact, and drive improvement across the food supply chain. Finally, large language models offer promising capabilities for expediting ontology creation, broadening inclusivity in ontology creation, and enhancing the accuracy of resulting data infrastructures.

1. Introduction

The reduction and repurposing of food that is lost or wasted throughout the food system presents a considerable opportunity to advance multiple private and public objectives including the reduction of environmental harms, the bolstering of food security, mining of value-added feedstock progenitors, and improvements of financial returns. Approximately one-third of all food produced globally is never ingested by a human (FAO, 2011), which has motivated the United Nations, national and sub-national governments, as well as private and quasi-private organizations to set goals to reduce food loss and waste (United Nations, 2015; US EPA, 2015; Pacific Coast Collaborative, 2018; Hardcastle, 2016; European Commission, 2020; Agri-Food Canada, 2020; Commonwealth of Australia, 2017; Stop Food Waste Australia, 2023).

Accomplishing these goals will require that private and public entities develop and maintain contextual knowledge about wasted foods and ingredients. Examples of this contextual information include the

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wasted material's biological source, quantity, composition, location (geographic and node in the food supply chain), destination (intended and actual), timing, intended purpose, environmental impact, and any causal antecedent actions in the production/processing/distribution that gave rise to the wasted product (e.g., sitting unrefrigerated too long). Defining food loss and waste (FLW) and developing a common, unambiguous language around FLW factors and contexts will enable specific, targeted actions aimed at FLW reduction and waste transformation and redirection toward higher-value alternatives (Babbitt et al., 2022; Corrado et al., 2019; Fabi et al., 2021, Hebrok and Heidenstrøm, 2019).

Currently, varied aspects of knowledge surrounding FLW are often held in siloed and proprietary data management systems administered across a multitude of heterogeneous actors including farmers, processors, distributors, retailers, waste haulers and municipalities that constitute or interact with modern food systems. And while consumer-facing technologies in the form of "smart" refrigerators and app-based shopping lists have emerged to combat this problem, a standardized common language akin to the way that HTML describes the contents of a web page, is yet to emerge for FLW. In addition to a common language, crafting and implementing initiatives to meet FLW goals can be facilitated with FAIR Guidelines where data meets standards for Findability, Accessibility, Interoperability, and Reuse (Wilkinson et al., 2016). The FAIR principles were crafted in response to society's increasing reliance on computational support to wield data in a world where data creation is proliferating, and the increasing necessity of such a lens for the food system is no exception (Top et al., 2022).

Increasingly important to the creation and maintenance of a FAIR data ecosystems is development and deployment of domain and application ontologies (Guizzardi, 2020). In computer science an ontology is a formal specification of entities, their associated definitions, and their relationships (Gruber, 2009). Unlike application programming interfaces (APIs) and data models, which require significant developer involvement, ontologies enable owners of heterogeneous, often siloed data systems to, "speak the same language" by "tagging" existing data items with preferred terms. This enabling of term concordance or "semantic clarity" without significantly altering their own data models or APIs, lowers barriers to FAIR data sharing by saving stakeholders great expense of needing to retool their application environment. The Gene Ontology is perhaps the most well-known biological ontology, built by scientists across the diversity of biological sciences—and without which the Human Genome Project could not have advanced (Ashburner et al., 2000).

As ontologies grow and are instantiated with data, they become a coordinated reservoir of unambiguous contextual knowledge created and curated by human domain experts that machine-led operations may draw upon to maximize their semantic integrity. Ontologies are particularly important for promoting the four FAIR pillars as the formalization of domain knowledge can allow disparate parties to know how best to search, find, synthesize, interpret and use relevant but disparate data (e.g., Beretta, 2021). In particular, because these functions are increasingly undertaken via automated and semi-automated approaches where humans' natural ability to contextualize and add meaning to data at each stage is non-existent or limited, ontologies become critical for contextualizing content to facilitate computer-powered semantics critical for functions like searches and data integration (Fensel, 2001).

The objective of this article is to review the literature that informs the creation, expansion or augmentation of ontologies that support efforts to reduce the amount or impact of FLW and to provide an outline for future development of ontologies in the food loss and waste domain. This includes reviewing and synthesizing extant articles that detail ontologies specifically designed to support FLW management as well as exploring the broader literature on ontologies to identify approaches and processes such as the use of artificial intelligence (AI) in the form of large language models (LLMs) that can support the development, refinement and maintenance of ontologies through time. The article concludes by suggesting future efforts to articulate and instantiate novel ontologies or expand extant ontologies relevant to organizing data relevant to global FLW reduction, recovery and valorization efforts.

2. Methods

The literature was reviewed following the process outlined in Fig. 1. All English-language articles published between January 1, 1990 and March 30, 2025 in journals indexed in either Scopus or Web of Science were eligible in the primary search. Additional articles or resources were identified either based on the authors' knowledge or through searches of references of articles identified in the primary search.

2.1. Literature review process

The search terms used in Scopus and Web of Science are detailed in the first row of Fig. 1. This combination of search terms yielded 3067 items from Scopus and 4562 items from Web of Science; when duplicates were removed, 6329 items remained.

Given the large number of remaining items that needed to be checked systematically, a Natural Language Processing (NLP) algorithm was implemented in Python (version 3.10) using the abstracts of all articles discovered in the search. This approach addressed the inefficiency and error-proneness of manual screening to ensure all relevant studies were identified (Wang et al., 2020) and adapts recent approaches to leverage NLPs to assist with complex reviews in other fields (e.g., Zdravevski et al., 2019; Zeng et al., 2022). The algorithm employed the Soft Cosine Measure, which was chosen for its ability to account for semantic similarities between terms and ensures a more nuanced and accurate identification of relevant studies (Sidorov et al., 2014). Each abstract was assessed against a core statement (see Fig. 1, row 4), which was developed by the authors, whose expertise spans food waste policy, food waste measurement, data science, food systems, and food ontologies.

We identified 542 items that obtained a score of 0.35 (on a 0 to 1 scale of similarity to the core statement), and these were considered for additional assessment. An author then reviewed each abstract and coded whether it contained at least one of the following key words/word roots: food, feed, waste, loss, 'ontolog'. Of the 17 articles that qualified, an author reviewed the documents and found that seven contained a data ontology relevant to FLW. Searching the citations of these documents and searching documents that cited these documents surfaced an additional article included in the synthesis, for a total of eight articles.

2.2. Literature analysis process

Authors reviewed articles identified by the process detailed in Fig. 1 for their purpose (reducing food waste, valorizing unwanted food, facilitating links among food system actors to support waste reduction), content, linkages/interoperability, ability to provide supportive contextual information, and adherence to accepted ontological practice. Results of these article reviews can be found in Tables 1 and 2. Authors subsequently mapped specific types of contextual information to each ontology, the results of which can be found in Table 3.

3. Results

Eight articles featuring relevant ontologies were identified (Table 1). The articles reference ontologies that vary with respect to their purpose (reducing food waste, valorizing unwanted food, facilitating links among food system actors to support waste reduction), adherence to accepted ontological practice, ability to provide supportive context, and interoperability. Two articles (Stojanov et al., 2019; Dimoski et al., 2020) revolve around the Food Waste Ontology, which was created as part of a European Union (EU) project addressing food loss and waste (REFRESH). Stojanov et al. (2019) depict and discuss the structure of the

Process Direction	Literature Sources	Scopus	Web of Science
	Initial Search Terms	(TITLE-ABS-KEY ((food AND waste) OR (food AND loss) OR (food AND recovery) OR (wasted AND food) OR rescue OR glean* OR (waste AND valoriz*) OR (food AND ingredient*) OR (food AND donat*) OR (food AND supply AND chain) OR (food AND component*) OR (donated AND food) OR food)) AND (TITLE-ABS-KEY (ontolog* OR (semantic AND web) OR (triple AND store) OR (resource AND description AND framework) OR (web AND ontology AND language) OR (process AND observation AND ontology) OR (supply AND chain AND ontology) OR foodon OR foodex2 OR foodwasteexplorer))	(TS=(food waste or food loss or food recovery or wasted food or food rescue or glean* or waste valoriz* or food ingredient* or food donat* or food supply chain or food component* or donated food or food)) AND TS=(ontolog* or semantic web or triple store or resource description framework or Web Ontology Language or Process and Observation Ontology or Supply Chain Ontology or FoodOn or FoodEx2 or FoodWasteExplorer)
	Returned documents	3067	4562
	Non-duplicated documents	6329	

Fig. 1. Literature search process.

Food Waste Ontology, which aims to support the valorization of different food waste streams. The authors then introduce a relational database informed by the ontology's structure and populated via a manual search of peer-reviewed articles by domain experts. The authors introduce a web-based interface designed according to Open Data principles (FoodWasteEXplorer) that permits manual online exploration of the database and enables machine-based data interoperability.

The Dimoski et al. (2020) article extends the contribution of Stojanov et al. (2019) by introducing a web-based tool named APRICOT (humAn-comPuteR InteraCtion tool for linking foOd wasTe) designed to help domain experts link elements from the food waste database introduced in Stojanov et al. (2019) to other data sets and ontologies. The interface facilitates the ability of a domain expert to enrich the existing database by suggesting candidate mappings to other resources, which the experts can then inspect and approve or reject. Alternatively, experts can inspect previously connected resources and remove inappropriate mappings as needed. The algorithm can suggest possible mappings between the elements of the existing database and elements in FooDB (https://dbpedia.org/ontology/Food) and query food and component names in sources including DBpedia (https://www.dbpedia.org/), FoodOn (https://foodon.org/) and SNOMED CT (https://www.snomed.org/). The authors then discuss their attempt at using the algorithm to map foods and components in the Food Waste Ontology to equivalent entries in FooDB using string matching, including challenges that surround choosing among multiple possible candidate mappings in FooDB or when the algorithm produces no candidate mappings.

Weber et al. (2023) details the development of PO2/TransformON, which is derived from the Process and Observation Ontology (PO2) to provide a vocabulary to support the transformation of food and bio-products, including those that may be excess or surplus to current needs and at risk of becoming food loss or waste. However, as an ontology capable of supporting the description of any biomass transformation process, PO2/TransformON supports use cases well beyond simply addressing food loss and waste. The authors designed the ontology by following the Linked Open Terms (LOT) methodology (Poveda-Villalon et al., 2022), which emphasizes re-use of existing ontologies and vocabularies to enhance interoperability. By leveraging both bottom up and top-down approaches, the authors collected ontological elements from at least seven extant OBO ontologies (e.g., FoodOn), the AGROVOC thesaurus (FAO), several classification systems (e.g., FoodEx2, European Waste Catalogue) with the process leading to the final product following a human-centered approach (Iqbal et al., 2013).

Barla et al. (2016) applies an ontological engineering approach to create the Waste Biorefinery Ontology (WBO) from the literature's received knowledge about how to apply various conventional and novel biorefinery processes to feedstocks (both from wasted food and from

	Statement constructed by authors to assess similarity to document abstracts using a Natural Language Processing algorithm that returns a normalized similarity score on a scale from 0 to 1	"Interoperable access to data on avoidable and unavoidable food waste is critical to facilitate exploration by researchers, industry, government, and the public to identify reduction strategies, improve valorization, and/or minimize environmental, financial, societal or nutritional impacts of discard. Food waste data is to be manually or passively collected and stored in a relational database. To enrich and make best use of data about wasted food and food scraps, we automatically transform the collected information into a new food waste ontology. The created Food Waste Ontology provides a formal description of knowledge from the food waste domain and relationships to adjacent ontologies, vocabularies, glossaries, taxonomies, and thesaurus for food, waste and valorization. Examples of its application are: (i) database querying based on natural language questions, and (ii) finding new or missing data from other datasets."
	Similarity score threshold applied to previous step	0.35
	# abstracts meeting or exceeding threshold	542
	# documents from previous step where key word search includes ('food' or 'feed') and ('waste' or 'loss') and 'ontolog'	17
	Documents returned after individual review by one co-author who searched for documents for a description of a data ontology applied to a food loss or waste setting	7 Baena et al., Barla et al.; Chesani et al.; Hollander et al.; Sanjeevi et al.; Stojanov et al.; Weber et al.
	Documents identified by searching references within the documents from the previous step or citations to the documents in the previous step	1 Dimoski et al., cites Stojanov et al.
	Total documents included	8

Fig. 1. (*continued*).

virgin sources) to create valuable intermediate and final products. Resources within wasted food streams are classified according to the dominant ingredient (e.g., cellulose, protein, sugars, etc.). The extant knowledge of input-output processes and their connections to key chemical components as encapsulated in the WBO could permit non-experts with appropriate software to query and retrieve valorization pathways for a given combination of waste and virgin resources using natural language. The potential for such a system is demonstrated by articulating potential valorization paths for five types of waste. While this approach holds great potential, at the current time there are no links to a larger database nor discussions of how the WBO may be connected to other ontologies.

Chesani et al. (2018) develops a decision support system to ensure that decisions to valorize wasted food within facilities created as part of the SORT project (a food systems sustainability project promoted by the Italian government) are both feasible and profit maximizing. The project will create facilities in Italy that receive food deliveries from large retailers and collection centers that would otherwise be sent to landfill. These deliveries are to be sorted into lots with similar characteristics that can be sent on for de-packaging and conversion into animal feed. The authors rely upon Constraint Logic Programming to ensure that sorting maximizes a facility's profits (value of sorted outputs less costs of sourcing and sorting incoming food shipments). This maximization accounts for how food items can be transformed into animal feed, and these constraints are embodied in the SORT ontology, which was created by drawing upon the definitions of feed materials and processes codified in the European Union's regulatory code (EU, 2017/1017). The authors test the constrained optimization system in simulated experiments of increasing complexity and assess the feasibility of identifying optimal solutions given the available computing power.

Sanjeevi et al. (2021) details a decision support system that relies upon an ontology to provide structure and is envisioned as part of an emerging Internet of Things (IOT) approach for agricultural and food supply chains. The system developed in this article is specific to a semi-automated post-harvest handling system designed to sort high-valued Sekai-Ichi apples by their quality using digital images captured within the system. The ontology is derived from previously captured apple images and informs the algorithm driving the sorting process. Improved sorting of apples can lead to less food loss, e.g., if poor quality apples are not removed they may cause high quality apples to deteriorate and be rejected at latter stages of the supply chain. The system provides another example of how a well-defined ontology can mobilize computational resources to achieve local system efficiencies. However, the ontology is highly localized to this specific task and

Table 1
Articles with ontologies related to food loss and waste.

Citation	Purpose	Contents	Linkages (Interoperability)	Contextual Information
Baena et al. (2020)	Support food waste **reduction** by family food businesses facing disruptions like COVID-19	An agent-based simulation leveraging an ontology of the beef taco supply chain among Guadalajara's taquerias	Not linked to any other ontology or database	None
Barla et al. (2016)	Bring knowledge of food waste **valorization** opportunities to non-experts	Waste Biorefinery Ontology structuring chemical and process relationships between inputs (waste and virgin) and potential outputs	Not linked to any other ontology or database	Feasible technologies and outputs of valorizing a particular excess feedstock
Chesani et al. (2018)	Develop a system to maximize profits when **valorizing** excess food.	A decision support system blending optimization algorithms with constraints informed by the SORT ontology developed from EU animal feed regulations	EU Regulation 2017/1017 on feed processing and feed categories	Animal feed stuffs feasibly produced with unwanted human food stuffs
Dimoski et al. (2020)	Automated mapping of food waste knowledge from different semantic resources to facilitate **valorization**	An algorithm to access and map knowledge from Stojanov et al. (2019) data set	Food Waste Ontology, FooDB, Dbpedia, FoodOn, SNOMED CT	Micro- and macro-nutrient profiles, compositional, biochemical, physiological characteristics, and allergens of wasted food items are potentially linked.
Hollander et al. (2020)	Characterize semantic links between food system actors that can facilitate outcomes such as **reducing** food waste	Process for stakeholder engagement to improve informatics frameworks including ontologies and the creation of the PPOD (persons-projects-organizations-datasets) ontology	VIVO ontology PPOD Ontology	NA
Sanjeevi et al. (2021)	Develop an Internet of Things (IOT) enabled system to support post-harvest apple sorting according to visual quality to **reduce** food loss	An algorithmically driven sorting system informed by an ontology of apple quality derived from accumulated photos captured in sorting system	Not linked to any other ontology or database	None
Stojanov et al. (2019)	Improve **valorization** of food waste via web-based tool FoodWasteEXplorer	Food Waste Ontology with 27,069 data points, 9 classes and 28 properties	Mapped to DBpedia. Can be linked to other ontologies	Macronutrients, inorganics (e.g., sodium), vitamin profile, bioactive compounds, and undesirable components (e.g., toxins) associated with wasted food items
Weber et al. (2023)	Provide a vocabulary designed for specific needs to describe transformation and **valorization** processes and characterize food, bioproducts, and biomass waste	PO2/TransformON with more than 5500 classes across food, feed, other substance, process and step branches	Specialization of the Process and Observation Ontology (PO2). Builds on FoodEx2 food classification system and European Waste Catalogue. Follows W3C format.	Functional properties of the raw unwanted food items and its primary derivatives, end products, and wastes or residues and the planned (e.g., pasteurization) and unplanned (e.g., decomposition) processes that can transform these food items

Table 2
Food Loss and Waste Ontology Practice Matrix.

Citation	Article publicly available?	Ontology publicly available?	Ontology Location	Ontology Findability	Ontology Design Principles	Upper Level Ontology	Last known update of ontology
Baena et al. (2020)	Open access	No	Could not find	Could not find	Could not find	Could not find	2020
Barla et al. (2016)	Paywall	No	Could not find	Could not find	Could not find	Could not find	2016
Chesani et al. (2018)	Open access	No	Could not find	Could not find	Could not find	Could not find	2018
Dimoski et al. (2020)	Paywall	No	Could not find	Could not find	Could not find	Could not find	2020
Hollander et al. (2020)	Paywall	No	Could not find	Could not find	Could not find	Could not find	2020
Sanjeevi et al. (2021)	Open access	No	Could not find	Could not find	Could not find	Could not find	2021
Stojanov et al. (2019)	Paywall	No	Could not find; links in footnotes are broken	Could not find	Could not find	Could not find	2019
Weber et al. (2023)	Open access	Yes	https://agroportal.lirmm.fr/ontologies/TRANSFORMON?p=classes	AgroPortal	OBO	Basic Formal Ontology (BFO)	2025

features no linkages to other datasets or ontologies, and hence does not necessarily contribute to broader food system interoperability.

In Baena et al. (2020) the authors construct a limited ontology to represent the supply chain of a prototypical beef taco truck business operating in Guadalajara, Mexico. The ontology serves a role similar to several of the previously reviewed articles in that it provides structure for a computationally intensive model. In this case, rather than an optimization-based model designed to achieve a narrow objective, the application features an agent-based model that simulates the amount of food wasted due to a disruption such as COVID-19 and the economic and environmental burden that such disruptions create. The article illustrates yet another way that ontologies can be used to structure tools, though the ontology itself is quite rudimentary and is unlikely to be re-used outside the exploratory structure of the authors' investigation or linked to other sources of information.

The Hollander et al. (2020) article does not introduce an ontology

Table 3
Food waste and loss ontology content.

Information Type	Baena et al. (2020)	Barla et al. (2016)	Chesani et al. (2018)	Demoski et al. (2020)	Hollander et al. (2020)	Sanjeevi et al. (2021)	Stojanov et al. (2019)	Weber et al. (2023)
Biological source	Yes, partially	No	Yes, partially	Yes	No	Yes, implicitly	Yes	Yes
Quantity	No	No	No	No	No	No	Yes	Yes
Composition	Yes, partially	Yes	Yes, implicit	Yes	Yes	No	Yes	Yes, implicit
Location	No	No	No	No	No	Yes, partially	No	Yes, partially
Destination	No	No	Yes, partially	No	No	No	No	No
Timing	No	No	No	No	No	No	No	Yes
Intended purpose	No	No	Yes, partially	No	No	No	No	No
Env. impact	No	Not yet but plans to do so	No	No	No	No	No	No
Causal antecedent	No	No	No	No	No	No	No	No

focused on food waste *per se*, but rather outlines an iterative process involving food system stakeholders that can lead to 'smarter foodsheds' where a foodshed describes the catchment area of the sources of food for a region. The process is envisioned as a means to produce semantic frameworks with greater interoperability that can help articulate the elements of a foodshed and underpin software technologies capable of identifying inefficiencies (such as FLW) that arise due to poor information flow across these regional systems. A key contribution of this article is the articulation of an ontology for foodshed stakeholder relationships named PPOD (persons-projects-organizations-data sets), which has high relevancy for any new or expanded ontology focused on food loss and waste. Following best practices, the ontology's classes and properties have largely been extracted from existing ontologies (e.g., VIVO, Corson-Rikert et al., 2012). The process detailed in the article can also serve as a template for future efforts to engage stakeholders to directly address gaps in existing food waste ontologies or to develop new ontologies that can inform policy and practices involving wasted food prevention, recovery and valorization.

Table 2 further reveals a critical gap in publicly available and well-structured ontologies within this domain. Of the eight studies analyzed, only one (Weber et al., 2023) provides a publicly accessible ontology, which is hosted on AgroPortal, follows OBO principles, and is based on the Basic Formal Ontology, a general ontological framework for understanding and representing

concepts across different fields. The remaining seven studies either do not provide an ontology or fail to offer a publicly accessible version. Furthermore, none of the non-public ontologies have clear documentation on ontology design principles, findability, or upper-level ontology alignment.

Table 3 further classifies the ontologies based on the type of information that they contain. As noted previously, contextual information about the wasted food material's biological source, quantity, composition, location, etc. is needed to meet the ambitious, cross-sector food waste goals outlined in the introduction. This table summarizes what already exists in this regard, and what is still lacking.

Across the reviewed ontologies, the most consistently represented forms of contextual information were *biological source* and *composition*, with six and seven ontologies, respectively, incorporating at least partial coverage of these categories. However, even here representation was uneven: several studies captured such attributes only implicitly (e.g., Chesani et al., 2018; Weber et al., 2023), while others offered only tiered or partial classification (e.g., Baena et al., 2020). By contrast, attributes critical for quantifying and tracing food waste flows—such as *quantity* and *location*—were rarely addressed, appearing explicitly in only two ontologies each. *Timing* of waste generation was captured exclusively by Weber et al. (2023), while *destination* and *intended purpose* appeared partially in a single ontology (Chesani et al., 2018). Dimensions of greatest policy relevance, including *environmental impact* and *causal antecedents*, were largely absent across the entire set, with only one study (Barla et al., 2016) noting environmental impacts as a future extension.

4. Discussion

The reviewed articles illuminate several ways that ontologies can inform private and public objectives surrounding food loss and waste. The first way is by codifying knowledge about how wasted food could be transformed into valued alternative uses (i.e., valorized) in a computationally accessible manner. Such efforts are undertaken in Stojanov et al. (2019), Dimoski et al. (2020), Weber et al. (2023), Barla et al. (2016) and Chesani et al. (2018). The ontologies in Stojanov et al. (2019), Dimoski et al. (2020) and Barla et al. (2016) were created with intensive input from domain experts who scoured the extant literature for critical information linking wasted food streams to relevant information. In contrast, the Weber et al. (2023) effort, while also human-centered, drew heavily on integrating extant knowledge sources that were already highly structured (e.g., other ontologies, vocabularies and classification systems).

Many of the efforts appear to have involved effort over a short period of time without structured processes to ensure updates, which may leave these ontologies subject to becoming outdated and of diminishing usefulness in systems that rely upon them. The exception is Weber et al. (2023), which have the PO2/TransformON posted to AgroPortal, a site containing a broad array of ontologies relevant to agri-food-related domains.

Other than Weber et al. (2023), none of these ontologies list an affiliation with a foundry, i.e., an organization where representatives of multiple ontologies with adjacent topics (e.g., biology, industry, behavior) agree to use one another's ontologies, adhere to common principles, and work together to revise affected ontologies to ensure interoperability. The Chesani et al. (2018) ontology may prove easier to update, however, as it is solely informed by EU animal feed regulations, which is highly structured and subject to regular revision due to governmental involvement.

Alternative to the "valorization" approach, FLW ontologies may structure existing sources of knowledge about the product quality (Sanjeevi et al., 2021) or the food supply chain (Baena et al., 2020) that can support altering or understanding system features that affect the amount of food that is wasted. These can range from highly technical and narrow ontologies derived from information gathered automatically within a local, defined system (Sanjeevi et al., 2021) to simple, stylized ontologies designed to structure indicative, bottom-up simulations of food system dynamics (Baena et al., 2020). These are both siloed ontologies with the Sanjeevi et al. (2021) work existing completely within a sensor and computational system designed for controlling the quality and losses of a single food item and the Baena et al. (2020) a simplified, bespoke ontology designed solely for illustrative purposes.

Alternatively, Hollander et al. (2020) introduce an ontology focused on food system stakeholders that can be wielded to facilitate participatory research processes that would be critical to structuring ontologies relevant to reducing food system inefficiencies such as food loss and waste. The ethos of the work by Hollander and colleagues embraces interoperability throughout the food system as a foundational goal, which is reflected by the use of classes and properties for the PPOD ontology drawn from previously established ontologies. While encouraging, PPOD is not itself affiliated with a foundry. Perhaps more importantly, the Hollander et al. (2020) work outlines an iterative stakeholder engagement process that can be wielded to address shortcomings to data interoperability, including the absence of ontological coverage of critical concepts related to FLW.

These findings in Table 2 highlight a significant lack of well-defined and openly accessible ontologies in the food waste sector, which poses challenges for interoperability, data integration, and knowledge representation in sustainability research. Addressing this gap requires the development and dissemination of robust, standardized ontologies that align with established principles and frameworks.

The majority of the reviewed articles (five of eight) focus only on ontologies that would support valorization, which is lower on the hierarchy of suggested activities for addressing food loss and waste while none explicitly focus on food recovery or rescue, and only a single study (Sanjeevi et al., 2021) explicitly addresses prevention. Baena et al. (2020) aspire to construct a model that would be useful to support food waste reduction and recovery efforts, but the ontology and modeling framework developed feature no elements that specifically inform such activities.

Patterns in Table 3 suggest that current ontology development has been primarily *data-driven*, emphasizing static descriptors of waste (source and composition) that align with readily available datasets. In contrast, more dynamic or process-oriented descriptors—including destination, timing, environmental impact, and causal antecedents—remain almost entirely unaddressed, despite their importance for cross-sector policy and systems-level interventions. The resulting ontologies therefore support only partial traceability of food waste flows, with limited capacity to inform prevention, redistribution, or impact assessment efforts. Notably, Weber et al. (2023) provides the most comprehensive framework, addressing nearly all categories, albeit often in implicit or partial form, and thus illustrates a potential foundation for integrating fragmented approaches into a more holistic system.

The absence of robust modeling for *quantity, timing, environmental impact,* and especially *causal antecedents* underscores a systemic blind spot that limits the utility of current ontologies for meeting global food waste reduction targets. Without explicit representation of these dimensions, it is difficult to support reproducible queries, cross-sector comparability, or evidence-based interventions. This highlights a critical opportunity for future ontology development: to move beyond cataloging waste "as it exists" toward frameworks that encode waste *as it happens*—capturing flows, destinations, and drivers in a machine-readable, interoperable manner. Integrating the partial efforts of studies such as Weber et al. (2023) with more domain-specific ontologies may provide a pathway toward such comprehensive coverage.

Approaches to addressing the issues of food loss and waste typically involve a hierarchy of activities (Fig. 2) that begins with reducing the amounts of food that are lost and wasted. Then, the focus shifts to recovering food that might be lost or wasted for audiences other than those initially targeted (e.g., secondary markets, emergency food system donations). Finally, valorizing lost and wasted food by creating products not intended for direct human consumption (e.g., animal feed, compost, biofuels) becomes the last step.

5. The path forward for establishing data interoperability in the food loss and waste space

Combatting food loss and waste will require improved computational and data infrastructures to overcome information systems that are

Fig. 2. The U.S. EPA's food waste scale.

often siloed across segments of increasingly complex food supply chains (Babbit et al., 2022). Data harmonization and interoperability will be essential if national and international goals are to be met. Some building blocks for such improved systems are available, including the extant food waste ontologies reviewed above, other related ontologies (e.g., FoodOn, Dooley et al., 2018), accounting and reporting standards for food loss and waste (Hanson et al., 2016), and proprietary ontologies (e.g., from food manufacturers, foodservice efficiency firms). The path forward should prioritize repurposing existing high-quality ontologies and vocabularies.

However, additional efforts to develop food loss and waste ontologies must work within a foundry (e.g., OBO) so as to provide the structure and discipline needed to adhere to principles common to the relevant adjacent ontologies and thereby ensure interoperability. To accomplish this, it will be critical to connect with key stakeholders through a structured process as suggested by Hollander et al. (2020). These key stakeholders would likely include food growers, food processors, food manufacturers, food retailers, transportation firms, emergency food system organizations, valorization firms, waste haulers, government agencies (e.g., FAO, USDA, FDA, NIST and EPA), information and search firms (Google), and information standardization organizations (GS1, ISO). The paucity of work focused on prevention and food recovery/rescue points to priorities for such conversations.

The creation and maintenance of ontologies can be time intensive, which requires significant funding and in-kind support to ensure the process is initiated and new ontologies are maintained and updated. As has been demonstrated in other domains (Toro et al., 2024; Kommineni et al., 2024; Hu et al., 2024; Kholmska et al., 2024), large language models (LLMs) present an innovative opportunity to support the development and refinement of ontologies in the wasted and lost food space. By leveraging LLMs' ability to process and synthesize vast datasets, the creation of high-quality, comprehensive ontologies can be accelerated. LLMs and can assist in the identification and integration of relevant terms, concepts, and relationships from existing sources, facilitating alignment with established standards (Food Loss and Waste Accounting and Reporting Standard, FoodOn) and proprietary ontologies.

In sum, addressing the complex challenge of food loss and waste at scale will require the collection, synthesis, and analysis of large data sets from multiple sources across the food supply chain. Identifying and optimizing novel solutions to the challenge will require computational approaches that can be applied across this heterogeneous data landscape. A robust ontology of food loss and waste concepts would help to accelerate the development and implementation of these approaches in the short term. In reviewing the literature, we found that while portions of food loss and waste ontologies have been developed for various scales and purposes, a broader and more universal ontology, informed by stakeholders and designed for interoperability with adjacent knowledge domains, is needed to enable advanced computational tools to support solutions to the global FLW challenge.

6. Conclusion and recommendations

This review reveals that while several ontologies address food loss and waste (FLW), most emphasize valorization, with little attention to prevention or recovery—the most effective interventions in the FLW hierarchy. Key contextual data such as quantity, timing, destination, environmental impact, and causal antecedents remain underrepresented, limiting their utility for comprehensive action. To advance this field, future efforts should prioritize ontology development within recognized foundries to ensure interoperability, actively engage stakeholders across the food system, and focus on underexplored use cases in prevention and recovery. Public accessibility, alignment with standards, and the integration of emerging tools such as large language models will be essential to accelerate development and foster inclusive, FAIR-aligned data ecosystems. By addressing these gaps, robust ontologies can provide the foundation for interoperable infrastructures that enable evidence-based interventions and support global food waste reduction goals.

CRediT authorship contribution statement

Matthew C. Lange: Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Methodology, Conceptualization. **Ran Li:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **John W. Apolzan:** Writing – review & editing, Writing – original draft, Investigation. **Patrick R. Huber:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Emily Steliotes:** Writing – review & editing, Investigation. **Kai Robertson:** Writing – review & editing, Writing – original draft, Software. **Norbert L.W. Wilson:** Writing – review & editing, Writing – original draft, Funding acquisition. **Karthik Jain:** Writing – review & editing, Software. **Rajiv Ramnath:** Writing – review & editing, Supervision, Funding acquisition. **Brian E. Roe:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Edward S. Spang:** Writing – review & editing, Writing – original draft, Resources, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors have no competing interests to declare.

Data availability

No data was used for the research described in the article.

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