Integrated Ontological Framework for Food Waste Prevention, Recovery, and Valorization

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Food Waste: Why are more and better ontologies needed?

- ~1/3 of food produced globally is never consumed → lost nutrition, money, and added GHG emissions
- SDG 12.3: halve per-capita food waste by 2030 → requires **comparable, interoperable data** across the supply chain
- **Today:** Food waste data are siloed by stakeholder (farms, processors, retailers, waste managers, policymakers)
- Need to be able to learn across other food/biology domains and answer questions like *"If a food is reused/upcycled, is it really considered waste"?*
- **Missing piece = shared semantic frameworks** to describe *what* is wasted, *where*, *how*, *why*, and *what is done about it*

"From Food Waste to Solutions" - 2025 ReFED Food Waste Report

Limitations of Existing Food Waste Ontologies

- **Over-focus on valorization**
  - Existing ontologies often model only downstream recycling/valorization
  - Prevention and recovery (donation, rescue) are underrepresented → misaligned with EPA's Wasted Food Scale (next slide)

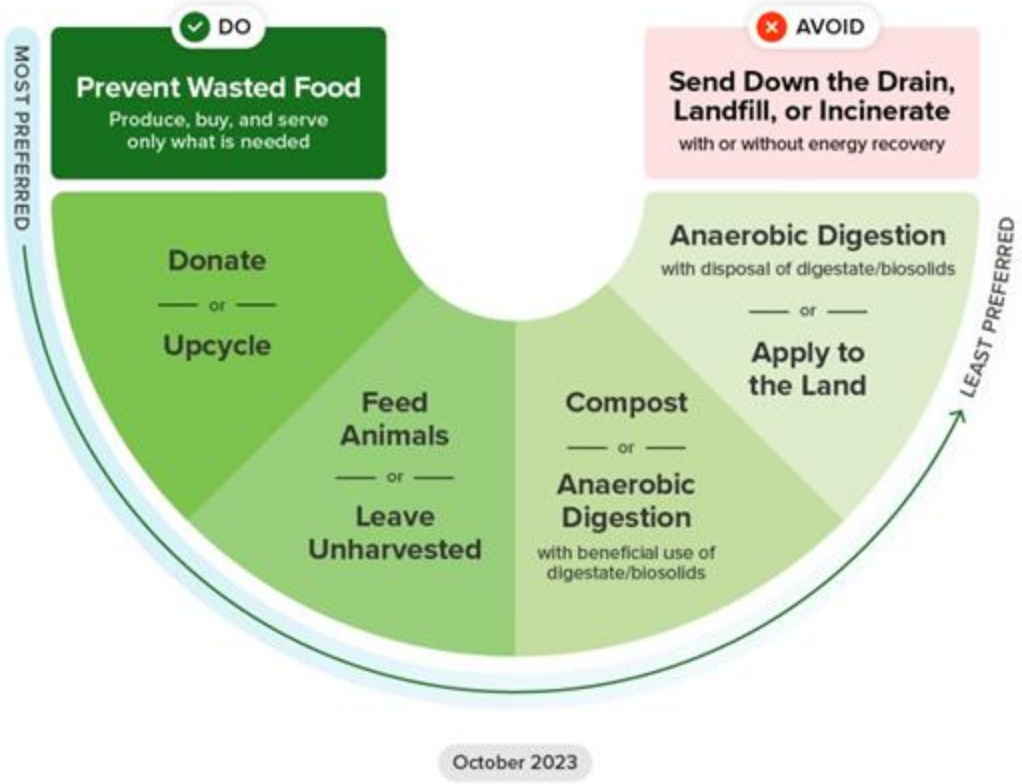
- **Static, not process-oriented**
  - Emphasis on categories of waste (type/source)
  - Weak modeling of flows, destinations, timing, and causal factors
  - Process-orientation important to describe the HOW

- **Limited interoperability**
  - Most developed in isolation, weak alignment with BFO/OBO Foundry and sector standards
  - Inconsistent definitions of "food loss", "food waste", "wasted food" (FAO vs. national agencies, etc.)

Matthew C. Lange, Ran Li, John W. Apolzan, Patrick R. Huber, Emily Steliotes, Kai Robertson, Norbert L.W. Wilson, Karthik Jain, Rajiv Ramnath, Brian E. Roe, Edward S. Spang,
Ontologies relevant for improving data interoperability for food loss and waste: A review and research agenda,
Cleaner and Responsible Consumption, 2025, https://doi.org/10.1016/j.clrc.2025.100330.

Wasted Food Scale

How to reduce the environmental impacts of wasted food



Our Contribution (and How It Extends Prior Work)

- A BFO-aligned **domain and application ontology** for food waste that:
  - Covers generation, prevention, recovery, and valorization
  - Centralizes **FoodWaste** as a material entity linked to both FoodOn and ENVO
  - Can be easily extended by those developing food waste prevention, transformation, and related processes

- Integrates and extends:
  - **OBO Foundry ontologies:** FoodOn, ENVO, RO, IAO
  - **Sustainability ontologies:** SCO, SDGIO, SuMSO, SDC

- Grounded in real-world standards and definitions:
  - FAO, USDA, ReFED, Upcycled Certified®

- Designed to support:
  - Cross-sector traceability and reporting
  - AI/LLM and linked-data applications

Ontology Design & Alignment: Methods Overview

- **Upper-ontology choice:** BFO → clear separation between material entities (e.g., FoodWaste) and processes (e.g., FoodWasteGeneration)

- **Reuse-first strategy:**
  - FoodOn → food materials/products
  - ENVO → waste materials, environments, treatment processes
  - RO → standard relations (part-of, has input/output, derives from)
  - IAO → information artifacts (datasets, reports, standards)

- **Sustainability context:**
  - SCO (SustainabilityObjective, Indicator)
  - SDGIO (targets and indicators, especially SDG 12.3)
  - SuMSO (patterns for supply chain stages and by-products)
  - SDC (environmental impact concepts, e.g., GHG emissions, LCA)

Core Concepts in the Integrated Framework

- **Material entity (continuant)**
  - ***FoodWaste*:** food material originally produced for human consumption, removed from the food supply chain
    - Subclass of **FoodOn:FoodMaterial** and **ENVO: FoodWaste, defined as "**A waste material which is primarily composed of uneaten food and removed from the food supply chain"
  - ***ValorizedProduct*:** material derived from FoodWaste (e.g., compost, biofuel, upcycled ingredients)
  - ***UpcycledFoodProduct*:** FoodOn food product with ≥ 1 ingredient **derivedFrom** FoodWaste

- **Processes (occurrents)**
  - ***FoodWasteGeneration*:** process that produces FoodWaste as an output
  - ***FoodWastePrevention*:** planned process reduces FoodWasteGeneration
  - ***FoodWasteRecovery*:** process where surplus/wasted food is diverted back to human/animal use
  - ***FoodWasteValorization*:** process converting FoodWaste into other valuable products/resources

Object Properties for Dynamic Waste Flows

- **hasWasteStream**
  - Domain: bfo:Process; Range: FoodWaste
  - "Process *hasWasteStream* some FoodWaste" → links generation/processing events to their waste outputs

- **derivedFrom** *(sub-property of RO:derives_from)*
  - Connects products/ingredients to their source materials
    Example: *BeerFromBread derivedFrom StaleBread* (StaleBread is FoodWaste)

- **eligibleForCertification**
  - Links entities (e.g., products) to certification schemes
    Supports modeling of criteria for Upcycled Certified® and other labels

- **hasDestination**
  - Connects FoodWaste (or waste streams) to destination categories (donation, animal feed, landfill, etc.)

- **hasCausalFactor**
  - Links FoodWasteGeneration events to causal antecedents (e.g., power outage, over-ordering, cold chain failure)

From Axioms to Inferences: An Upcycling Example

- **Key axiom (simplified):** *UpcycledFoodProduct ⊑ FoodProduct ⊓ (derivedFrom some FoodWaste)*

- **Scenario:**

  Individual `:StaleBread` typed as FoodWaste
  Individual `:BeerFromBread` typed as FoodProduct
  Assertion: `:BeerFromBread derivedFrom:StaleBread`

  If-then reasoning: If a FoodProduct **derivedFrom** some FoodWaste → reasoner classifies it as *UpcycledFoodProduct*

- **Extension for certification:**

  Add data/axioms for "≥10% ingredients derivedFrom FoodWaste" and documented diverted mass
  If criteria satisfied → assert *(or reason over)* `eligibleForCertification UpcycledCertifiedProgram`

- **Demo outcome:**

  OWL reasoner infers `:BeerFromBread rdf:type UpcycledFoodProduct`
  - Shows how ontology supports rule-like "if-then" behavior without bespoke rule engines

Evaluation & Testing (Planned)

- **Logical consistency checks**
  - Reasoner-based validation (e.g., HermiT/ELK) on the integrated ontology
  - Verified no unsatisfiable core classes (e.g., FoodWaste, UpcycledFoodProduct, process classes)

- **Competency questions (examples):**
  - “Which processes generate FoodWaste at the retail stage?”
  - “Which products qualify as UpcycledFoodProduct given their ingredient provenance?”
  - “For a given city, what are the destinations of vegetable FoodWaste?”

- **Prototype instances:**
  - Stale bread → upcycled beer (upcycling & certification example)
  - Gleaning events, donation programs, and composting facilities for recovery/valorization flows

- **Planned/ongoing evaluation:**
  - Expert review sessions with food sustainability and ontology engineers
  - Mapping of at least one real FLW dataset to test usability and completeness

Lessons from Reusing FoodOn, ENVO, and Sustainability Ontologies

- **Overlapping / slightly different definitions**
  - Example tension: multiple notions of “food waste” across ENVO, FAO text, and policy usage
  - Strategy: adopt ENVO’s class as the formal anchor, and capture FAO/USDA nuances via textual definitions and annotations

- **Different modeling patterns**
  - Some ontologies represent supply chain stages as processes; others as roles or locations
  - Strategy: choose a consistent pattern under BFO (e.g., processes + roles) and map external terms into that pattern

- **Granularity mismatches**
  - FoodOn is very detailed on food types; less detailed on “waste” status
  - SuMSO detailed for meat sector; we generalize patterns to broader FLW

- **Mitigation approaches:**
  - Prefer *reusing* and constraining existing classes rather than minting new near-duplicates
    Use `owl:equivalentClass` `skos:exactMatch`, or `closeMatch` mappings where appropriate
  - Document known modeling decisions so others can extend/align consistently

From Ontology to Data & AI

- **Standards-based reporting**
  - FLW Accounting Standard destinations and quantity patterns embedded in the ontology
  - Supports FLW-compliant datasets and dashboards (mass removed, destination, edible vs. inedible portions)

- **Decision support & scenario modeling**
  - Represent “waste as it happens”: causes, destinations, and interventions
  - Queryable scenarios: “What if we invest in prevention vs. valorization?”

- **AI and LLM integration**
  - Ontology acts as a **knowledge graph backbone** grounding LLM responses in clear semantics
  - LLMs can help annotate legacy food waste datasets with ontology classes/relations
  - Potential synergy with biomass transformation and LCA ontologies for full life-cycle assessments

Ontology Coverage & Granularity (In progress)

- **Upper-level coverage is broad; depth varies and is intentionally left extensible**

- **Coverage by branch (examples):**
  - *Materials*: FoodWaste, InediblePortion, ValorizedProduct, UpcycledFoodProduct
    - Strong coverage via FoodOn + ENVO; extended for upcycling & inedible parts
  - *Processes*: Generation, Prevention, Recovery, Valorization; basic subclasses defined
    - Future work: richer catalog of specific prevention/valorization techniques
  - *Destinations & causes*: FLW Standard destinations, causal factors modeled as separate classes
    - Gaps: finer-grained behavioral/organizational causes (e.g., contractual practices, demand forecasting)

Availability & Future Work

- **Ontology access:**
  - Public URI / persistent link: **coming soon!**
  - Machine-readable formats: TTL + OWL
  - Brief technical summary will be added to paper: number of classes, properties, axioms, imports

- **Axiomatization roadmap:**
  - Refine logical definitions for FoodWaste, FoodWastePrevention/Recovery/Valorization, UpcycledFoodProduct
  - Tighten property domains/ranges (e.g., derivedFrom as sub-property of RO:derives_from)

- **Future collaboration:**
  - Link with other food waste frameworks and ontologies presented today
  - Deepen alignment with emerging food, biomass, and LCA ontologies
  - Co-development of sector-specific extensions (e.g., household waste, institutional catering, specific commodities)

Thank you!

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