The Interoperability Challenge in Waste Management: An Ontological Approach

Elena Milivinti

University at Buffaalo, Department of Philosophy, NY, United States of America

Abstract

Inconsistent definitions of 'waste' across international organizations create critical data interoperability barriers that undermine efforts towards global coordination of waste management. This paper examines definitional fragmentation among EU, OECD, and UNEP frameworks, using EU textile waste management as a case study. Current waste definitions treat *waste* as an intrinsic material property analogous to mass or density, thereby failing to capture the contextual nature of the designation of something as waste. In this communication I propose a formal ontological framework based on Basic Formal Ontology (BFO) that reconceptualizes waste as a context-dependent role rather than a material characteristic. The framework distinguishes between the inherent dispositions of material entities, their designed functions, and assigned roles within specific contexts. Using the BFO framework, we define waste as a role assumed by a material entity when (a) its designed function is no longer fulfilled, (b) there exists an intention of disposal, and (c) there is no economically viable alternative realization of the entity's dispositions is realizable within the given context. This approach provides machine-readable, universally applicable classification standards that enable standardized exchange of waste management data while accommodating jurisdictional variations. The proposed framework offers a foundation for resolving international classification discrepancies and advancing circular economy initiatives through improved data interoperability.

Keywords

Waste Management, Ontology, Data Interoperability, Basic Formal Ontology, Waste Classification

1. Introduction

The global waste crisis is rapidly escalating, with projections indicating a surge to 3.8 billion tonnes by 2050, from 2.3 billion tonnes in 2023 [1]. This necessitates the development of efficient and sustainable waste management strategies. While smart cities increasingly leverage data analytics to optimize waste streams, a critical barrier remains: the lack of data interoperability [2]. Inconsistent definitions and classifications of waste across national and international jurisdictions (including EU, OECD, and UNEP) create data silos, hindering effective analysis and policy implementation. This problem is particularly acute in the textile sector [3], a significant contributor to global waste with an estimated 16 million tonnes of textile waste generated annually within the European Union alone [3]. The revised EU Waste Directive in May 2018, requires EU Member States to establish systems for separate collection of textile waste by 1 January 2025 [4] highlights the urgency of this challenge. However, the current fragmented approach to textile waste management across member states, stemming from inconsistent classifications and data reporting systems creates significant obstacles [5]. Different interpretations of the European Waste Catalogue (EWC), coupled with varying national implementations and supplementary subcategories, lead to irreconcilable datasets, hindering accurate cross-border comparisons and effective EU-level policy development and implementation [5].

This paper argues that a refined ontological framework for waste classification is crucial to overcoming this interoperability challenge. By explicitly defining and relating key concepts such as waste, resource, byproduct, and residue using a formal ontology like the Basic Formal Ontology

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* Corresponding author.
: emilivin@buffalo.edu (E. Milivinti)
: 0009-0008-1739-5105 (E. Milivinti)

(BFO) we can create machine-readable, consistent data representations. This will facilitate more effective data analysis, improved policy development, and ultimately, a more sustainable and circular textile economy within the EU and beyond.

2. The Case for Ontology in Waste Management

2.1. Challenges in Textile Waste Management Across European Countries

In the European Union only about 25% of the textiles is collected for recycling and the rest primarily end up in landfills or incineration facilities [3]. Despite ambitious targets set by the EU's Circular Economy Action Plan and the requirement for separate textile waste collection by January 2025 [4], textile waste management remains fragmented across member states [5]. This fragmentation stems in part from differing collection infrastructures, but a more fundamental problem derives from the inconsistent classification, definition, and data reporting systems used for textile waste [5].

The pervasive nature of these definitional inconsistencies is exemplified even in official data presentations. For instance, the explanatory notes for Textile waste generation across European countries based on Eurostat's ENV_WASGEN dataset [6] explicitly acknowledge fundamental methodological limitations: "As there is no harmonised method for Waste Collection Authority (WCA) across Europe, these numbers should be interpreted cautiously. There are no data available on textiles in mixed municipal waste for Türkiye ... due to a lack of capacity, Ireland and Norway were not able to verify these data ... Italy indicated that its figure for waste from economic activities is an overestimation as it includes non-textile waste like scraps from leather manufacturing or secondary textile waste" [6]. These caveats reveal that even when attempting to present standardized European textile waste data, researchers must acknowledge that the underlying classification and measurement systems are so inconsistent that direct cross-country comparisons become unreliable.

This data limitation requires cautious interpretation of the aggregated data due to the lack of harmonized waste composition analysis methodologies across countries [5]. Even when countries collect textile waste data, the methods are so different that direct comparisons become nearly impossible [5]. For instance, how one country defines and measures textile waste might differ substantially from another's approach [5]. This variability could lead to significant discrepancies in understanding the true scale and nature of textile waste generation and management. This observation highlights a critical challenge in waste management research: the inherent variability in data collection and analysis methods. The acknowledgment of data collection and analysis methodology demonstrates the complex nature of cross-border waste management data management.

The European Waste Catalogue (EWC) provides a standardized framework for textile waste classification across the European Union.

Table 1
EWC Codes for textile waste

EWC Code	Description
04 02	wastes from the textile industry
04 02 09	wastes from composite materials (impregnated textile, elastomer, plastomer)
04 02 10	organic matter from natural products (for example grease, wax)
04 02 14*	wastes from finishing containing organic solvents
04 02 15	wastes from finishing other than those mentioned in 04 02 14

04 02 16*	dyestuffs and pigments containing hazardous substances
04 02 17	dyestuffs and pigments other than those mentioned in 04 02 16
04 02 19*	sludges from on-site effluent treatment containing hazardous substances
04 02 20	sludges from on-site effluent treatment other than those mentioned in 04 02 19
04 02 21	wastes from unprocessed textile fibres
04 02 22	wastes from processed textile fibres
04 02 99	wastes not otherwise specified
15	WASTE PACKAGING; ABSORBENTS, WIPING CLOTHS, FILTER MATERIALS AND PROTECTIVE CLOTHING NOT OTHERWISE SPECIFIED
15 01 09	textile packaging
19 12	wastes from the mechanical treatment of waste (for example sorting, crushing, compacting, pelletising) not otherwise specified
19 12 08	textiles
20	MUNICIPAL WASTES (HOUSEHOLD WASTE AND SIMILAR COMMERCIAL, INDUSTRIAL AND INSTITUTIONAL WASTES) INCLUDING SEPARATELY COLLECTED FRACTIONS
20 01 10	clothes
20 01 11	textiles

Note: Codes marked with asterisk (*) indicate hazardous waste

The fragmentation of textile-related codes across multiple primary categories – industrial waste (04), packaging and protective materials (15), mechanical treatment waste (19), and municipal waste (20) – creates systematic barriers to comprehensive textile waste tracking and analysis.

This categorical dispersal hinders several interoperability problems. First, aggregating total textile waste data requires querying disparate database sections, as there is no unified textile waste category that encompasses all material flows. Second, the classification system exhibits inconsistent granularity levels, with industrial textile waste (04 02) offering detailed subcategorization including specific codes for composite materials, finishing processes, and fiber types, while municipal textile streams are broadly categorized as simply "clothes" (20 01 10) or "textiles" (20 01 11) without further specification.

Furthermore, the EWC's mixed classification approach – combining source-based categories (industrial versus municipal origin) with material-based distinctions (processed versus unprocessed fibers) – introduces ambiguity in waste stream assignment. A textile item may transition through multiple EWC codes during its waste lifecycle, but the system provides no mechanism for tracking these transitions or maintaining material flow continuity. This structural limitation becomes particularly problematic when attempting to implement circular economy monitoring or trace material pathways for Extended Producer Responsibility[1] schemes, as the classification system cannot adequately capture the dynamic nature of textile waste processing and recovery operations.

1 The Extended Producer Responsibility requires producers to take responsibility for their products' entire lifecycle, including post-consumer waste management, generating funding for recycling infrastructure and data to support environmental targets.

The challenge goes further when examining textile export procedures [7], where the Combined Nomenclature (CN) system – the EU's standardized product classification framework for trade declarations – intersects with waste management regulations. The CN framework categorizes exported used textiles through two principal codes: 6309 for worn clothing and textiles, and 6310 for textile rags and scraps in both sorted and unsorted forms. While the theoretical distinction appears straightforward – 6309 encompassing materials suitable for second-hand markets versus 6310 covering items destined for industrial applications or deemed unsuitable for direct reuse – the practical implementation reveals significant classification ambiguities.

A critical gap emerges from the absence of a dedicated CN code for textile waste exports, despite textiles being explicitly listed on the EWC. The authorities must evaluate whether exported textiles constitute waste materials, typically correlating with CN classifications where 6309 items are rarely designated as waste while 6310 materials face potential waste classification. However, the reality of export practices often involves large volumes of unsorted textile shipments containing diverse categories – household linens, industrial textiles, technical fabrics, clothing accessories, and mixed fiber compositions – that likely span both CN classifications, undermining the classification system's precision and creating uncertainty about the true nature of exported materials. The challenge emerges when a single export shipment might be classified as CN 6310 for trade purposes, yet contain materials that would be categorized across multiple EWC codes (20 01 10 for clothes, 20 01 11 for textiles, 04 02 21 for unprocessed fibers) if they remained within the EU waste management system. The inability to reconcile these parallel classification systems means that textile materials effectively "disappear" from waste tracking systems upon export, making it impossible to accurately assess whether the EU is meeting its circular economy targets or merely displacing its textile waste problem to other regions.

2.2 Consequences of Data Inconsistencies

The neighbour-check[2] study [5] highlights the significant challenges posed by the current fragmented and inconsistent approaches to textile waste management across Europe. The study reveals a lack of clarity concerning the scope of the revised Waste Framework Directive [4], which does not define what is to be included under 'textiles' in the requirement for separate collection by 1st January 2025. Specifically, it is unclear which categories of textile products are included and whether the separate collection extends beyond household textiles to encompass industrial and commercial sources.

Table 2

Adapted from *Towards 2025 - Separate Collection and Treatment of Textiles in Six EU Countries* (Miljøstyrelsen, 2020).

	Denmark	Finland	Sweden	France	Netherlands	Germany
Collection over the counter in second-hand shops where textiles are checked through on delivery.	Not waste	Not waste	Not waste	Not waste	Not waste	Not waste
Kerbside collection and bring-banks where the collector clearly communicates that it ONLY receives clean, undamaged and reusable textiles.	Not waste	Not waste	Not waste	Not waste	Waste	Waste

2 A neighbour check is a comparative analysis where countries examine similar nations' regulations and practices to identify needed adjustments in domestic law or implementation [5].

Kerbside collection and bring-banks where the collector communicates that all types of textiles may be delivered.	Waste	Waste	Waste	Waste	Waste	Waste
Indoor collection in a retailer where the collector clearly communicates that it ONLY receives clean, undamaged and reusable textiles.	Not waste	Not waste	Not waste	Not waste	Unclear	Waste
Indoor collection in a retailer where the collector communicates that all types of textiles may be delivered	Waste	Waste	Waste	Waste	Waste	Waste

Table 2 reveals fundamental inconsistencies in how European countries classify textile collection activities, with some nations treating all collected textiles as waste regardless of their reuse potential, while others distinguish between waste collection and resource recovery based on intended end-use. Such divergences create significant challenges for cross-border material flows, regulatory compliance, and data reporting, ultimately undermining accurate measurement of progress toward EU waste management targets deriving from the incompatible recording methodologies across member states.

Existing classifications, often fragmented and jurisdiction-specific, fail to capture the inherent complexity of textile materials and their diverse end-of-life scenarios. By explicitly modeling the material properties of textiles (fiber type, weave, colorfastness), their intended functions (as clothing, upholstery, industrial fabrics), and the available recycling technologies (mechanical, chemical), an ontology can facilitate the integration of diverse data sources and support the development of more efficient and sustainable waste management strategies.

The mentioned examples illustrate why an ontological approach, by establishing shared definitions, classification hierarchies, and data exchange standards, is essential to addressing the interoperability challenges in textile waste management across Europe. When one country classifies leather jackets as textile waste, another categorizes them separately, the resulting data inconsistencies cascade throughout the entire waste management value chain. These inconsistencies are not merely academic concerns; they translate into substantial economic and environmental costs.

3. The Babel of Waste: Inconsistencies in Global Waste Definitions

3.1. Waste: A Dynamic Concept

As the textile waste case study has demonstrated, different definitions lead to significant data inconsistencies that undermine effective waste management and policy coordination. For this reason, I will examine how 'waste' has been defined by major international organizations. Each governing body – the EU, OECD, and UNEP – provides distinct definitions that are influenced by varying priorities, creating the definitional fragmentation exemplified in our remarks above

Table 3
Definitions of Waste

Institution	Definition	Weaknesses

EU [8]	Any substance, material or object which the holder discards or intends or is required to discard.	Subjective interpretation based on the intentions or obligations of the holder (e.g. materials abandoned without intent may fall outside the definition).
OECD [9]	Materials that are not prime products (i.e., products produced for the market) for which the generator has no further use for production, transformation, or consumption, and for which he wants to dispose.	May exclude waste with noneconomic implications.
UNEP [10]	Substances or objects that are disposed of, intended to be disposed of, or required to be disposed of by the provisions of national law.	Introduces inconsistencies due to varying national regulations, leading to different classifications of waste across countries.

Defining waste through the act of discarding raises two fundamental questions about value. Does the object itself lose inherent value through the act of discarding [9]? Or is the perceived loss of value merely a function of its context, a temporary state that can be reversed through re-use or re-purposing? These questions highlight two distinct perspectives: a contextual view, which emphasizes the situational and subjective nature of value, and a material view, which focuses on the intrinsic properties of the object and its potential for future use regardless of its current context. The phrase 'Waste isn't waste until we waste it' captures an essential truth: waste is not an intrinsic property of materials but rather a context-dependent designation. Waste is a dynamic concept shaped by context, purpose, and perceived value. While often viewed as an endpoint, waste can be a temporal stage, a resource waiting to be recontextualized. The thriving second-hand clothing market and the practice of recycling demonstrate this transformative potential. Even on a global scale, the value of waste value is fluid, as seen in Sweden's import of waste for energy production, generating both revenue and a reduction in fossil fuel dependence.

Current definitions of waste fail to capture its dynamic and context-dependent nature. The resultant static view hinders effective waste management, overlooking the potential for reuse, recycling, and recontextualization. By recognizing waste as a fluid designation, capable of transformation through processes like recycling, we can unlock new opportunities for sustainability.

The United Nations Environment Programme and International Solid Waste Association's 2024 report explicitly recognizes this challenge:

> Definitions are a cornerstone in the development of legislation at all levels. ... Definitions of waste and different types of waste, as well as how these definitions are applied, vary internationally, including within regions or countries. This may be due to different interpretations of terminology, lack of standardised categories, differences in legal, regulatory, and policy frameworks, and major conceptual and methodological challenges concerning the observation and measurement of waste [9].

Given the fundamental role that definitions play in developing policies and achieving international cooperation and standardization, particularly in collaborative domains like waste management, we believe it is essential to adopt an ontological approach that begins with establishing clear definitional foundations. The current lack of standardized waste definitions hinders effective global cooperation, demonstrating the need to return to first principles. By grounding our approach in the Basic Formal Ontology (BFO) as a foundational framework, the next section will explore how we can build robust and universally applicable definitions of waste from the ground up, providing the conceptual clarity necessary for international interoperability.

4. An Ontological Framework for Waste Classification

4.1. Basic Formal Ontology (BFO) as a Foundation

BFO (Basic Formal Ontology) is a top-level ontology, and it's designed to provide a foundational framework for representing knowledge across various scientific domains. Unlike domain-specific ontologies that focus on a particular area (e.g., medical ontology, biological ontology), a top-level ontology aims to establish a common set of fundamental categories and relationships that can be used to integrate data from diverse sources [11]. This integration is crucial for facilitating interoperability and knowledge sharing across different scientific disciplines. BFO achieves this by providing a structured vocabulary and a set of formal axioms that define the relationships between different types of entities.

BFO provides a robust framework for defining and relating key concepts that are essential for understanding waste classification. As a top-level ontology, BFO establishes fundamental categories and relationships that can be applied across domains. For building a definition for waste in BFO terms, we believe it is important to examine three core concepts. First, we must consider Independent Continuants, which are material entities that exist independently and persist through time while potentially undergoing changes in their properties and relationships. Second, we need to understand the concept of Role, which represents a realizable entity that exists because there is some single bearer that is in some special physical, social, or institutional set of circumstances in which this bearer does not have to be and which is not such that, if it ceases to exist, then the physical make-up of the bearer is thereby changed. Third, we should examine Disposition, which is a realizable entity such that if it ceases to exist, then its bearer is physically changed, and whose realization occurs when and because its bearer is in some special physical circumstances, and this realization occurs in virtue of the bearer's physical make-up. Finally, we must also consider Function, which is a disposition that exists in virtue of the bearer's physical make-up and this physical make-up is something the bearer possesses because it came into being either through evolution (in case of natural biological entities) or through intentional design (in the case of artifacts), in order to realize processes of a certain sort.

To illustrate how these BFO concepts apply to waste classification, consider an aluminum can. The can itself is an independent continuant, the material entity that persists through its lifecycle. It can possess several dispositions inherent to its material properties: the disposition to conduct electricity, to be malleable, and to resist corrosion due to its aluminum composition. These dispositions remain constant regardless of the can's current use or status.

The can's function, i.e, to contain beverages, derives from its intentional design and manufacture. This function represents the purpose for which the can was created and reflects the specific physical design features (cylindrical shape, sealed construction, pop-top mechanism) that enable it to fulfill this intended purpose.

However, the can's role is context-dependent and can change throughout its lifecycle. Initially, it may have the role of "beverage container" when filled with beverage and sold. From there, when discarded by the consumer, it might transition to the role of "waste". Alternatively, it could assume the role of "recyclable material" when placed in recycling systems, or even "raw material" when processed back into aluminum stock.

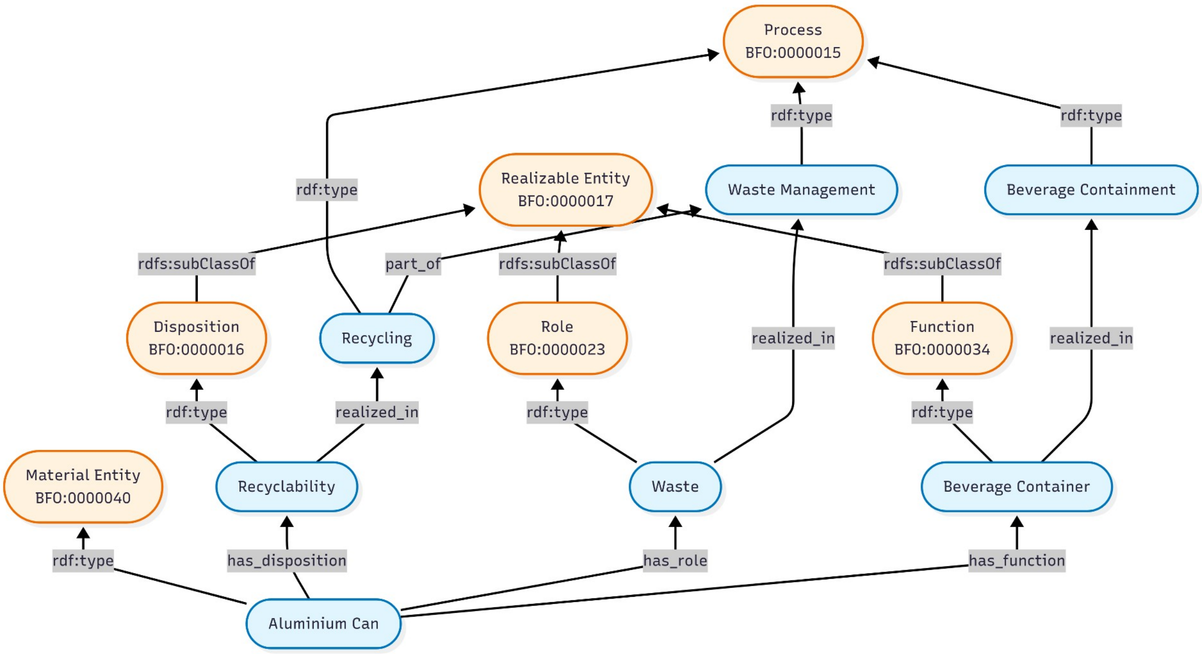

Figure 1: Ontological representation of a material entity lifecycle using BFO framework.

Figure 1 demonstrates the ontological structure connecting an aluminum can with its realizable properties in waste management contexts. The diagram uses two distinct visual categories: orange nodes indicate BFO (Basic Formal Ontology) classes including Material Entity, Process, Disposition, Function, Role, and Realizable Entity, while blue nodes represent domain-specific classes and instances.

The aluminum can exemplifies a Material Entity that possesses three distinct realizable entities. First, it has an inherent recyclability disposition that becomes actualized during recycling processes. Second, it assumes a waste role when participating in waste management activities. Third, it fulfills a beverage container function through beverage containment processes. These realizable entities demonstrate how the same physical object can simultaneously embody multiple ontological aspects depending on the processes in which it participates. The hierarchical relationship between recycling and waste management processes illustrates how specific activities can be components of broader operational frameworks.

Relationship types include: rdf:type (instantiation), rdfs:subClassOf (taxonomic hierarchy), has_disposition/has_role/has_function (property attribution), realized_in (actualization of potentials), and part_of (mereological relationships). This pattern exemplifies how BFO can be applied to model the multiple simultaneous roles, functions, and dispositions of material entities throughout their lifecycle, providing a formal foundation for circular economy and waste management ontologies.

4.2. Defining Waste in BFO Terms

Building upon the BFO conceptual framework, we can now develop a comprehensive definition of waste that accounts for its multifaceted and dynamic nature. The challenge lies in capturing how the same material entity can transition between different roles while maintaining its inherent dispositions and original function.

The context-dependent nature of waste becomes evident when we consider how perceived value shifts with technological advancement and economic conditions. Electronic devices once considered waste are now valuable sources of rare earth minerals, while materials treated as waste in regions lacking recycling infrastructure become valuable resources when exported to places where such technologies exist. This variability demonstrates that waste classification cannot rely solely on material properties but must incorporate contextual factors.

Using BFO's role-based framework, we can formalize this contextual nature by recognizing that waste assignment depends on the interplay between a material's inherent dispositions, its designed function, and the prevailing socio-technical context. This approach avoids the definitional ambiguities present in current international frameworks while maintaining the flexibility necessary to accommodate diverse waste management scenarios.

A material entity (independent continuant) assumes the role of waste within a specific spatiotemporal context when: (a) its designed function is no longer fulfilled, (b) there exists an intention of disposal, and (c) there is no economically viable alternative realization of the entity's dispositions is realizable within the given context.

This definition captures the essential elements identified in existing international frameworks while addressing their limitations. The reference to "designed function" accommodates the EU's focus on intended use, while "economically viable alternatives" addresses the OECD's market-oriented perspective. The contextual constraints acknowledge the UNEP's recognition of varying national implementations without being bound by specific legal frameworks.

Table 4

BFO Formalization Support for Existing Waste Definitions

Institution	Definition	BFO Formalization Approach
EU	Any substance, material or object which the holder discards or intends or is required to discard.	Substance/material/object: independent continuant. Holder: agent role. Discarding: process.
OECD	Materials that are not prime products (i.e., products produced for the market) for which the generator has no further use for production, transformation, or consumption, and for which he wants to dispose.	Materials: independent continuants. Prime products are defined by their intended function within market processes. Generator: agent role. Production, transformation, consumption are formalized as specific relations between agents and materials.
UNEP	Substances or objects that are disposed of, intended to be disposed of, or required to be disposed of by the provisions of national law.	Substances/objects: independent continuants. Disposal processes are formalized with clear start and end conditions.

Table 4 focuses on how BFO can provide the formal foundation needed to address the limitations identified in existing institutional definitions. BFO's structured approach offers the conceptual tools to transform informal definitions into precise, machine-readable specifications while maintaining their core meaning and regulatory intent.

For the EU definition, we can formalize the subjective aspects of "discarding" and "intention" by explicitly modeling the relationships between holders, materials, and contextual factors. The framework can represent the conditions under which abandonment occurs, even without explicit intent, by defining abandonment as a process that results in a change of role assignment.

The OECD definition's focus on economic utility can be formalized through BFO's disposition and function categories. Materials can be modeled as having economic dispositions that may become inactive or unfeasible within specific contexts, leading to waste role assignment. This approach addresses the limitation of excluding non-economic implications by allowing for multiple simultaneous considerations in role assignment.

For the UNEP definition's reliance on national legal frameworks, BFO provides a foundation for representing legal contexts as spatiotemporal regions with specific normative properties. This enables the modeling of jurisdiction-dependent waste classifications while maintaining a unified underlying structure that facilitates cross-jurisdictional data integration.

The ontological approach thus provides a formal foundation that can accommodate existing definitional approaches while offering a path toward standardization and interoperability. By representing the underlying logical structure of waste classification, BFO enables the development of mapping tools that can translate between different definitional frameworks while preserving semantic consistency.

5. Conclusion and Future Work

This paper demonstrated the critical need for a standardized, interoperable approach to waste classification, highlighting the significant challenges posed by inconsistent definitions and data reporting across international organizations and within the EU. These findings establish a foundational case for developing formal ontological frameworks in the waste management domain, where the complexity of material life cycles, the diversity of stakeholder perspectives, and the need for cross-jurisdictional data integration create an environment where *ad hoc* definitions and classification systems are required for effective policy implementation and technological solutions.

By proposing a refined ontological framework based on BFO, this paper addresses the dynamic and context-dependent nature of waste while providing the formal structure necessary for machine-readable classifications. The analysis of textile waste management across European countries clearly demonstrates how definitional inconsistencies create cascading problems throughout the waste management value chain. Future work will involve:

- Developing a comprehensive domain-specific ontology for waste management based on the BFO framework, incorporating insights from existing waste management ontologies and technical artifact research;
- Creating mapping tools to connect existing classification systems to the standardized ontology, facilitating transition from current fragmented approaches;
- Testing the framework with real-world textile waste data to validate its practical applicability;
- Extending the ontology to different waste streams;
- Collaborating with policy makers and industry stakeholders to ensure the ontological framework addresses practical implementation challenges.

The adoption of an ontological approach is not merely a technical solution; it is a crucial step towards achieving the ambitious sustainability goals set by international organizations and individual nations, paving the way for a more efficient and environmentally responsible future for waste management.

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Declaration of Generative AI

The author has not employed any Generative AI tools.

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