ClimOO: Towards a Suite of Ontologies for Plastic Pollution and Climate Change

Giorgio A. Ubbiali[1,*], Ludger Jansen[1,2]

[1] PTH Brixen College, Piazza seminario 4, 39042 Bressanone, Italy
[2] University of Rostock, Universitätsplatz 1, 18055 Rostock, Germany

Abstract

To date, plastic pollution and climate change represent pressing global challenges that necessitate immediate intervention to promote sustainability worldwide. Considering this urgency, disparate standards and metrics, aimed at addressing such interconnected challenges, have been developed both globally and locally. On one hand, this variety ensures dealing with those phenomena in detail and according to various stakeholders' needs. On the other hand, such resources are usually designed in a siloed manner, resulting in a lack of interoperability among related data, which largely limits the benefits deriving from this multiplicity of views. Modeling knowledge into logically structured vocabularies, ontologies can assist in addressing this need for interoperability. This paper introduces the architecture of the ClimOO ontology suite, a set of nested ontologies dedicated to model plastic pollution, climate change, and their mutual interrelations, presenting current ontology design status.

Keywords

Plastics, plastic pollution, climate change, sustainability, ontology, COSMOS

1. Introduction

Plastic pollution has emerged as a major issue threatening both global sustainability and human health. Plastic debris is considered to be nearly ubiquitous around the globe and is able to move through ecosystems, altering their structures and properties along with biogeochemical cycles, such as carbon and nitrogen cycles [1–3]. Plastic litter can be ingested or inhaled by living organisms, causing swallowing, entanglement, and tissue damage [4, 5]. Microplastics — in the most extensive sense defined as plastic debris smaller than 5 mm — are able to penetrate organisms' bodies, including the human body, increasing inflammation responses, cell oxidative stress and tumor incidence, while also impacting organism growth and cellular metabolisms [6–9].

Plastic pollution has been proven to be interconnected with other current global challenges, such as climate change [1, 10]. Greenhouse gas (GHG) emissions are produced along the entire plastic life cycle, largely contributing to global warming. In 2019, GHG emissions from plastic life cycle counted for about 1.8 gigatons (Gt) of carbon dioxide (CO2) equivalents (3,7% of total global emissions); and increases in temperatures, extreme weather events, and drought stimulate plastic debris degradation, fostering the release of contaminants as well as microplastic accumulation and mobility across terrestrial and aquatic ecosystems [10].

Across fields of study and communities, there exist varying sustainability standards and metrics of reference for plastics and climate, tackling particular nuances of those phenomena along with adapting to specific contexts, stakeholders, and purposes [9, 11–14]. Nevertheless, these resources are usually designed in a siloed manner. The terminologies used diverge, with associated meanings and interpretations often varying across stakeholders. They also generally lack attention to the intrinsic interconnection between plastic pollution and climate change. This comes with an increased

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* Corresponding author.
giorgio.ubbiali@pthsta.it (G. A. Ubbiali); ludger.jansen@pthsta.it (L. Jansen)
0000-0001-7872-1770 (G. A. Ubbiali); 0000-0002-0097-6359 (L. Jansen)

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risk of misinterpretation and hinders data exchange and interoperation across communities, ultimately limiting the benefits deriving from using together such standards and metrics.

Ontologies have now been consolidated as efficient instruments to address the need for semantic clarity and data interoperability. Ontologies systematize knowledge into standardized vocabularies of terms and relations, complemented by logical axioms, common definitions, and univocal identifiers, offering clear and coherent understanding of endorsed meanings and the semantics employed [15–17]. Generally implemented in machine-interpretable and computable languages, such as Web Ontology Language (OWL), ontologies also promote data interoperability and exchange across stakeholders that adopt them.

To date, however, limited and disconnected ontology efforts exist with regard to sustainability [18]. In particular, no ontology exists that effectively deals with plastic pollution and its mutual interrelations with climate change. To fill this gap, we are designing the ClimOO ontology suite. The ClimOO ontology suite is a set of nested ontology modules, modeling plastics, plastic pollution, climate change, and their interrelations. The ClimOO ontology suite is intended to support the interoperability for data about plastic pollution and its impact on climate change. This paper reports on the current status of this resource.

The remainder of this paper is organized as follows. Section 2 reviews main ontologies dealing with plastic pollution and climate change. Section 3 presents the methodology we are adopting to create the ClimOO ontology suite. Section 4 describes PlasticO, the currently complete module. Section 5 presents the next planned steps. Ontology files and other materials can be found in the ClimOO GitHub at https://w3id.org/climoo/.

2. Background

Currently, there is no ontology specifically dedicated to plastics and plastic pollution. Certain resources, such as AGROVOC [19] or the Biodiversity Thesaurus [20], include some terminology referring to plastics, but do not provide a comprehensive account. Some ontologies are implemented for plastic-related use cases, such as TransformON/PO2 [21], an ontology representing biomass transformations, that includes an application to bio-composite processing for food packaging, or the work of López that proposes an initial model for olive oil supply chains and applies it to describe the life cycle of plastic bottles along these supply chains [22]. Some further ontologies, such as the Environment Ontology (EnvO), an ontology modeling environmental and anthropogenic systems, biomes, habitats, and related processes, and the Chemical Entities of Biological Interest (ChEBI), an ontology representing chemical entities, of relevance for organisms, provide initial not-exhaustive accounts of plastics and plastic pollution [23, 24]. Finally, the Platform Material Digital Core Ontology (PMDco) is a mid-level ontology for the domain of material sciences and engineering [25]. PMDco specifically models, materials such as thermosetting and thermoplastic material, related properties, processes, and related analysis.

For climate and climate change, several semantic resources are available. Some of these resources focus on these topics per se, such as the Climate Analysis (CA) Ontology [26] and the Climate and Forecast (CF) vocabulary [27]. Others address climate, climate change, and related features, in relation to specific domains, such as EnvO with respect to environmental systems. There is the HEritage Resilience Against Climate Events on Site (HERACLES) Ontology [28], modelling cultural heritage and its preservation from climate change, and the Climate Smart Agriculture (OntoCSA) [29] that deals with transforming agricultural systems to face climate change. Further, there are also resources dealing with relevant related topics , such as OntoAgroIdro [30] covering consequences and impacts of climate change and agricultural activities on water resources, and the Climate Crisis Management Ontology [31] centering on managing crises deriving from climate change, such as natural disasters. Yet, no ontology models the interconnection between plastics and climate. The Sustainable Development and Climate (SDC) Ontology specifically focuses on representing climate and climate change, accounting for the related impacts on water, food, and energy systems [32]. SDC ontology specifies its model in relation to the Sustainable Development Goals (SDGs), in particular

SDG 1 (no poverty), SDG 2 (end hunger), SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy), and SDG 13 (climate action). However, plastics and climate change ontologies have been developed mostly in separation, and in general appear lacking in interoperability, with the exceptions of those reusing common upper-level ontologies, such as Basic Formal Ontology (BFO).

3. Methods

To develop the ClimOO suite, we used the methodology introduced by Ubbiali et al. (2026) to develop the Sustainable Meat Systems Ontology (SuMSO) [33] that integrates established and widely recognized ontology design methodologies and bodies of best practices, such as METHONTOLOGY, OTK methodology, and Open Biological and Biomedical Ontology (OBO) Foundry principles [34, 35]. The SuMSO methodology distingusihes (1) project setting, (2) ontology participatory design, and (3) ontology maintenance. In the following, we will describe the design process of the ClimOO ontology suite consisting in the first two phases.

3.1. Project setting

Project set up: By assessing relevant literature and engaging with stakeholders, we delineate the ClimOO domain, identified main terminology and Competency Questions (CQs), and envisaged ontology applications.

Assessment of existing resources: We explored Google Scholar for literature on sustainability, climate change, and plastic pollution, focusing on publications related to agriculture, employing the following combinations of keywords (search conducted in Italy in June 2025): “Climate Change” and “Agriculture, Plastics and Microplastic Pollution” and “Agriculture”; “Climate Change” and “Plastic and Microplastic Pollution” and “Agriculture”; “Sustainability” and “Climate Change” and “Plastics and Microplastics”; “Sustainability” and “Climate Change” and “Plastics and Microplastics” and “Complex Systems” and “Agriculture”. For reasons of feasibility, we limited our assessment to the first 50 results, focusing on the most recent publications; we also performed the searches including “2025” as a search term. We complemented this pool of resources with literature stakeholders referred us to and private materials stakeholders shared with us and the first 20 results of search for “climate change” on PubMed and for “Climate Change, plastics, and panarchy” and “plastics, types, review” on Google Scholar.

We applied the same search procedure to assess relevant ontological resources. The combinations of keywords used are the following (search conducted in Italy in June 2025): “Ontology” and “Sustainability”; “Ontology” and “Sustainable Development”; “Ontology” and “Climate Change”; “Ontology” and “Plastics”; “Ontology” and “Microplastics”; “Ontology” and “Plastic Pollution”; “Ontology” and “Plastic Pollution” and “Climate Change”; “Ontology” and “Plastic Pollution” and “Agriculture”; “Ontology” and “Climate Change” and “Agriculture”; “Ontology” and “Plastic Pollution” and “Climate Change” and “Agriculture”. In addition, we used the keywords “plastic(s)” and “climate (change)” to manually explore the List of Sustainability Ontologies [18], AgroPortal [36], EcoPortal, EarthPortal, BiodivPortal [37], OntoBee linked data server browser [38, 39], and OntoUMLs Catalog [40]. Attention was primarily dedicated to well documented resources that are part of the BFO ecosystem, such as OBO Foundry.

3.2. Ontology participatory design

Stakeholders’ identification and engagement: The primary stakeholders of this work are three research institutes active in the Province of Bolzano–South Tyrol (Italy) that are involved in and contribute to the ClimOO project, a regional project exploring the potential contributions of South Tyrolean agriculture to mitigate climate change and face (micro)plastic pollution. Stakeholder engagement included discussions with representatives from each stakeholder institute about the ontology goal and domain of interest, emphasizing views and frameworks of reference regarding sustainability, agricultural systems, plastic pollution, climate change, and related assessment methods. To facilitate

the discussions, we provided stakeholders with background materials, including draft models and lists of terminology and questions. Together with institute representatives, we formulated potential Competency Questions (CQs) that the ClimOO ontology suite should be able to answer and terminology to include, focusing on types of plastics and plastic debris, plastic object used in agriculture, and processes interconnecting plastic pollution and climate change. The list of questions and the resulting CQs are documented in the ClimOO repository.

We engaged with institute representatives either in person or online. Italian and English were the languages spoken. We recorded online meetings and documented conversations to establish a basis for further articulating a common narrative. The meeting syntheses have been revised and anonymized; they are available in the ClimOO repository. Discussions were often continued by email.

Project narrative formulation: We built up ClimOO's shared narrative step by step while performing stakeholders' interviews. After each meeting, we revised and integrated syntheses of the discussions into a unifying account. We identified perspectives and frameworks of reference, and pinpointed and accommodated similarities and divergences concerning sustainability, plastic pollution, climate change, and agricultural systems. We integrated insights from established literature and standards of reference. The shared narrative is available in the ClimOO repository.

Ontology construction: We identified the ClimOO vocabulary while constructing the shared narrative. We collect relevant terminology from literature, materials shared by stakeholders and their recommendations. We analyzed relevant existing ontologies and selected suitable classes for import. We complemented the ClimOO vocabulary with definitions, formulated, again, according to stakeholders' suggestions and the literature assessed. We formatted the vocabulary and definitions according to best practice rules recommended by Arp et al. and Smith [15, 41]. In parallel, we hierarchically organized the vocabulary and formalized it in OWL, using Protégé and Visual Studio Code. At this stage, we modularized the ClimOO ontology suite. We collected ontology imports in OWL either manually or using OntoFox tool. We followed a middle-in approach to design the ClimOO ontology suite, i.e., we used BFO as a guideline to assess the domain content suggested by stakeholders and literature and organized it under BFO as a top-level ontology[42].

Ontology validation: We run ELK and HermiT reasoners via Protégé plug-in, performing automatic reasoning. No inconsistencies were detected. Stakeholders validated the ClimOO ontologies, confirming that the model matches their needs and expectations.

4. The ClimOO ontology suite

ClimOO is a suite of ontologies that models plastics, plastic pollution, climate change, and their interrelations and mutual influences. It is intended to support interoperability of data on plastics, plastic pollution and climate, with a particular focus on agriculture, including data from the ClimOO project, such as data from soil sample analyses, normative data, and data on plastic usage in agriculture. Main envisaged users include ontologists and computer scientists interested in such domains and, more broadly, agriculture experts and practitioners. Emphasis is mainly dedicated to types of plastics and plastic debris, related properties and pollution, deriving threats and mutual contribution to climate change. with a focus on agricultural systems as potential contributors or affected fields, with apple production systems in South Tyrol (Italy) as the main use case. The ClimOO ontologies are formalized in the Web Ontology Language (OWL) and encompasses English as natural language. It conforms to the OBO-Foundry principles [43] and FAIR principles, and is licensed under CC BY 4.0. The following four modules will be included in ClimOO ontology suite (Fig. 1):

- Plastic Ontology (PlasticO) is designed as a reference ontology for the plastic domain to represents polymer molecules, plastic materials, pieces of plastic, plastic objects, as well as plastic life cycle and pollution processes.

- ClimOO-SDC2 is a fork and update of the SDC Onto model of weather, climate, and climate change to integrate into the ClimOO suite.
- Plastics Interconnecting with Climate Change Ontology (PICCO) extends PlasticO and ClimOO-SDC2 to model mutual interconnections between plastic pollution and climate change.
- PICCOmela enriches the PICCO model with regards to agriculture systems, especially apple production.

All ClimOO modules extend BFO and the Sustainability Core Ontology (SCO), a mid-level ontology dealing with sustainability to foster model consistency [18]. They also import from several other ontologies, mainly from the BFO ecosystem, including EnvO, SDC Ontology, and PMDco, to reuse existing resources related to plastic pollution, climate change, and agriculture, especially from the BFO and OBO Foundry ecosystems. A complete list of imported resources is provided in the ClimOO repository. The ClimOO ontologies equally align with several plastic frameworks, including the works of [12, 13, 44–47], several EU and Italian standards and regulations, such as the BS EN 13432:2000 standard for packaging, and the EU Commission Regulation 2023/2055, and regional references, such as the Bioland Südtirol guidelines and the L'Agenda 2030 del Consorzio Vini Alto Adige. Centro di competenza per il vino dell'Alto Adige. Consult the ClimOO shared narrative for a complete list.

ClimOO-SDC2 is nearing completion. We are updating SDC on the model concerning environmental features and impacts of climate change, and adapt it with respect to SCO and the ClimOO suite. In parallel, we are collecting and preparing terminology to be covered in PICCO and PICCOmela. In the next section, we will describe the PlasticO module, which is already complete to date.

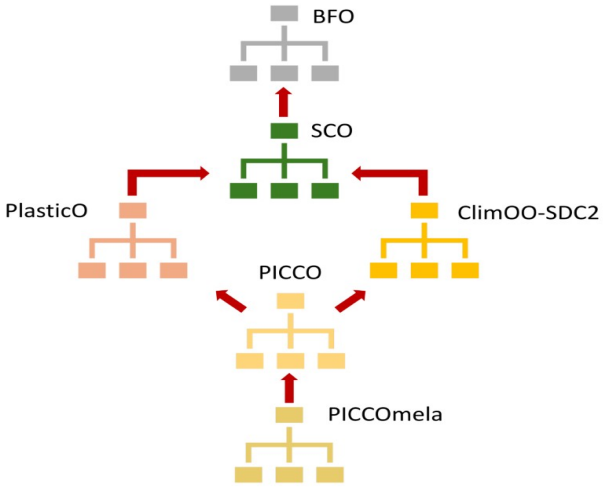

Figure 1: ClimOO ontology suite architecture and upper-level ontologies. Arrows indicate the importing direction ("imports from").

4.1. PlasticO

Here, we dedicate each subsection to describe one of the aforementioned themes modeled whitin PlasticO. We proceed as such for reasons of clarity. PlasticO integrates all these segments into a single model. For Figures 2–4, we use the following nomenclature: blue boxes = PlasticO classes; light-blue boxes = BFO classes; orange boxes: classes from the Core Ontology for Biology and Biomedicine (COB); ⟶ **(bold)** = subsumption relation to the immediate upper-level class; ⟶ (dashed) = subsumption relation not to the immediate upper-level class; ⟶ (dark red) = other relations;. The ontology acronyms are shown close to classes and relations. All diagrams have been created using CmapTools.

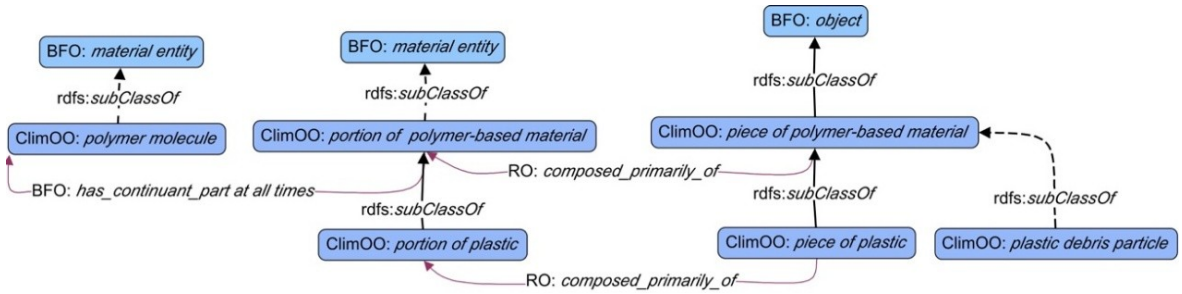

Figure 2: Polymer molecules, plastic materials, plastic pieces and debris in PlasticO.

4.1.1. Polymer molecules, pieces, materials, objects and debris

PlasticO contains a range of classes of material entities to model the plastic domain which we justify in depth in [48]. To start with, polymer molecules are long chains of macromolecules. They generally derive from polymerization processes, but may also derive from degradation of longer chains [12, 46, 47]. Monomers, in contrast, are molecular entities bearing a disposition to polymerize, while polymerization processes are converting monomer molecules into polymer molecules, realizing the monomers' disposition to polymerize. PlasticO reuses classes from ChEBI with respect to polymer molecules. Portions of polymer-based material (often referred to as polymeric materials) are material entities made up of polymer molecules (Fig.2), usually combined with further molecules, such as additives in synthetic polymer-based materials. Portions of plastic are portions of polymer-based material with a disposition to become soft and pliable when heated and solidify afterward (thermoplasticity), or to become rigid once cured (thermosetting) [12, 45]. PlasticO reuses classes from ChEBI, PMDco, and EnvO with respect to portion of polymer-based materials. Pieces of plastic are bona-fide boundary objects having as part portions of corresponding materials (Fig.2), while plastic objects, in the common sense of the term, are pieces of plastic made or used to fulfill a certain function. Plastic debris is a solid piece of polymer-based material, insoluble in water, persistent and mobile in the environment, and not used for a purpose anymore (Fig.2).

4.1.2. Plastic life cycle

The life cycle of plastics spans from polymer extraction and production, transportation, usage, consumption, and disposal. To illustrate our modelling of the life cycle stages, we will briefly discuss plastic production and usage.

Plastic production encompasses the manufacturing of portions of plastic and related pieces and objects. The first are planned processes that have as a primary output a portion of synthetic plastic, while the second are planned processes that have some portion of synthetic plastic as the main input and some piece of synthetic plastic as the main output. Plastic manufacturing processes cover some synthetic polymerization processes as part. Feedstocks from which plastic polymers derive can be fossil fuels or bio-based, such as biomasses [49, 50].

Plastics are used across sectors and fields [49]. The usage of synthetic plastic pieces is a planned process employing pieces of synthetic polymer-based material for some purpose. Usage of synthetic plastic pieces occurs causally downstream or within manufacturing processes of synthetic plastic pieces (Fig.3). EnvO models plastic manufacturing processes. We did not reuse EnvO's model of plastic manufacturing processes because it is misleading insofar plastic manufacturing processes should be restricted to the production of synthetic human-made plastics, but EnvO axiomatization refers generally to production of all plastics (including natural plastics).

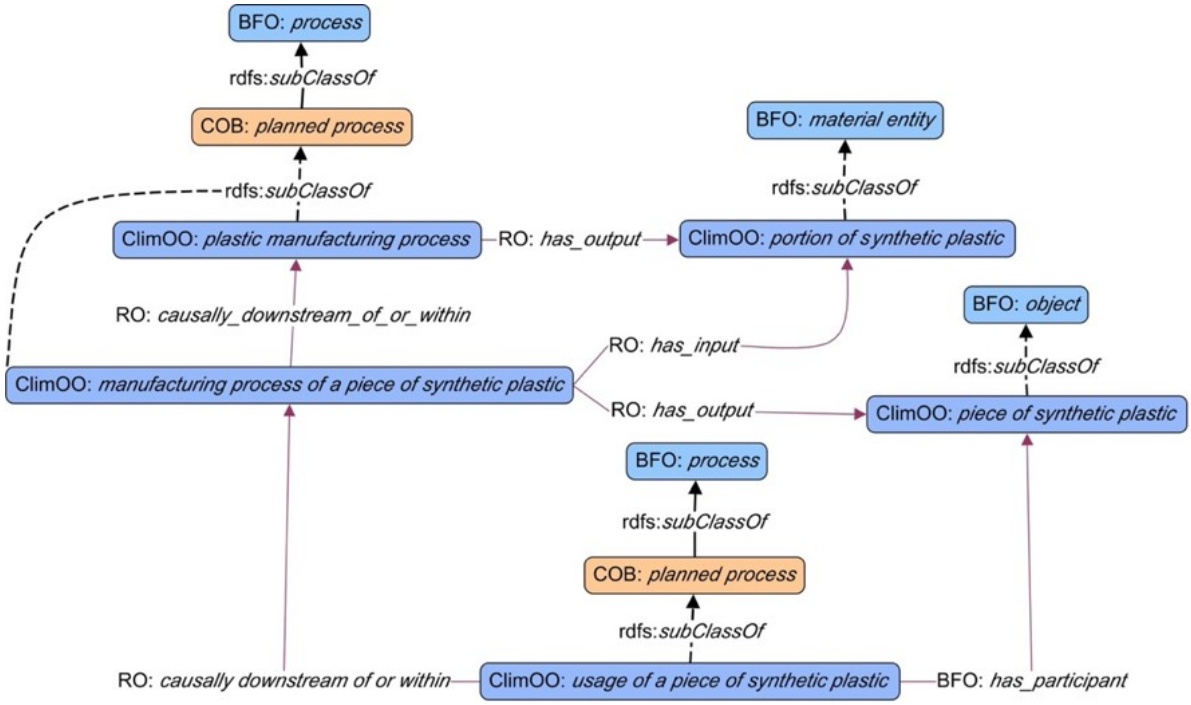

Figure 3: Plastic manufacturing and usage in PlasticO.

4.1.3. Plastic pollution

Improper and harmful practices and behaviors throughout the entire plastic life cycle can lead to the occurrence of plastic pollution, which is modelled in ecology and environmental sciences as the flow of material from a pollution source to some sink environments. PlasticO models plastic pollution processes as processes during which plastic debris particles are released into (and possibly accumulated in) an environment, from some plastic debris source to some plastic debris sink, affecting the structure and properties of the environment as well as those of the related system components [3, 4, 7, 51, 52]. Plastic debris sources are material entities that have as part some polymer-based synthetic material and bear the role of debris sources realizing in plastic pollution processes. Plastic debris sinks are material entities (normally not a portion of plastics or polymer-based synthetic material) that bear the role of debris sink realizing in plastic pollution processes (Fig.4).

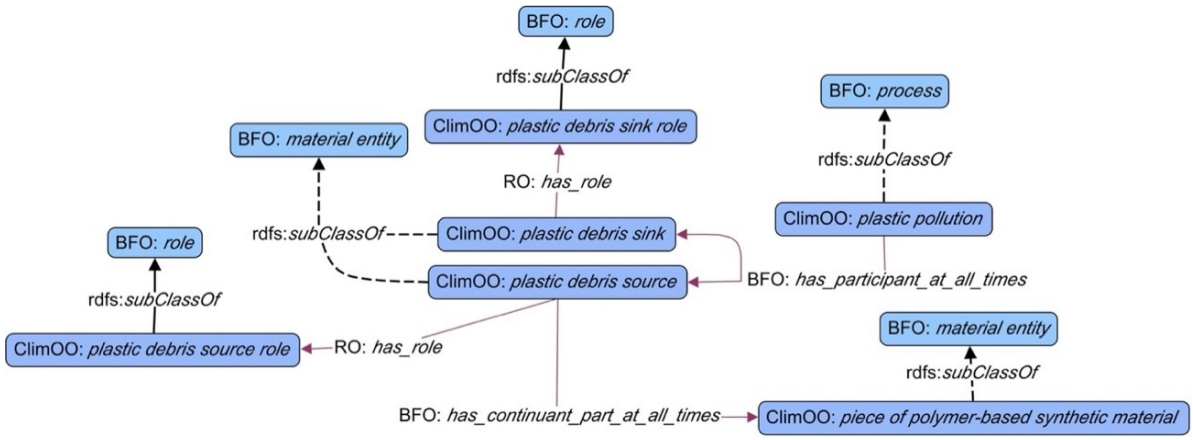

Figure 4: Plastic pollution and plastic debris in PlasticO.

5. Discussion and conclusion

Developing an ontology suite for plastic pollution and climate change comes with several challenges. First, this endeavor brings together topics from different levels of analysis and granularity, ranging from polymer chemistry to global climate science. This does not only involve distinct scientific disciplines dealing with those topics, but often different cross-disciplinary views and approaches to such topics. Microplastics, for example, can be viewed from the perspective of chemistry, but also from the perspective of environmental sciences, where the first emphasizes the material composition while the second is rather interested in its origin as plastic debris. We created classes distinguishing plastic materials and pieces in terms of polymeric composition, and a debris class with a larger range of applicability than those of plastic classes to harmonize such views for sustainability purposes.

In addition, reusing and importing classes from existing ontologies to foster interoperability has been a challenge when confronted with partial and inadequate representations. Possible solutions include (1) suggesting a modification to the source ontology, (2) importing the class without changing it, (3) importing the class without changing it but treating it as if changed, (4) importing the class and changing it – possibly by creating an "overlay" file with changed class to shield off the change (a strategy suggested by John Beverley in correspondence), and (5) creating a new class while referencing or mapping, if possible, to the inadequate class. The first approach would be best, but source ontologies might lack maintenance, the ontology curators and the related community may not be responsive, or the ontology may serve particular use case scenarios resulting in reluctance to revise the ontology. Further, changes in a well-established ontology may require a lot of time before being approved and incorporated. The remaining approaches bypass engaging with source ontology curators and communities. However, the second approach leads to a lack of domain adequacy; the ontology would import an inadequate class and perpetuate the insufficient model. The third approach leads to a lack of semantic stability and integrity across ontologies; different ontologies would treat the same class differently, potentially leading to issues with data annotation and interoperability. The fourth approach would also lead to interoperability problems, especially if a third ontology would import from both source and target ontologies. Such an approach might be viable for application ontologies, but not for reference ontologies that are intended to be reused together with other OBO Foundry ontologies. The fifth approach leverages creating a new class that presents adequate axiomatization and mapping it to the inadequate class via SubClassOf or EquivalentTo. This approach ensures semantic integrity, promotes domain adequacy, while preventing interoperability issues as much as possible. Nevertheless, it requires multiplying resources and models, limiting import and reuse. In light of these considerations and our experiences, ontology design, we are adopting the first approach, and when communities are not responsive, we opted for the fifth, introducing interim classes that could be obsoleted when the envisioned revision of the already existing class has been implemented.

ClimOO-SDC2, PICCO, and PICCOmela are still work in progress. Thus, the next planned steps are to finalize the term collection and the domain modelling for these modules as well as the governance of the suite architecture. We also aim to assess (and possibly import from or align with) additional resources, such as ContaminOSO [53]. In parallel, we plan to strengthen the validation process by requiring further approval from stakeholders, creating error probe classes and individuals, and interrogating the ClimOO ontology suite for CQs via SPARQL queries. As the primary use case for the ClimOO ontology suite is the "Climate, Plastics and Sustainability: Ontology and Operationalisation (ClimOO)" project, we foresee using the ClimOO ontology suite to connect data within this project and with other relevant projects on plastic pollution and climate change.

The ClimOO ontology suite will be publicly available on GitHub at https://w3id.org/climoo/repo and will integrate efforts towards establishing a Community of Common Ontologies, Semantics, and MOdels for Sustainability (COSMOS) that will contribute to its curation and maintenance [18].

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Declaration on Generative AI

During the preparation of this work, the authors used Grammarly and the Free AI Paraphrasing Tool to check grammar and spelling, paraphrase, and reword. After using these tools, the authors reviewed and edited the content as needed and took full responsibility for the publication’s content.

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