

Evaluating End-of-Life Scenarios for Satellites Using Life Cycle Assessment

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Abstract

As the number of satellites in orbit continues to grow, the end-of-life (EoL) phase of spacecraft presents critical challenges for orbital sustainability and environmental responsibility. Current EoL strategies, such as natural reentry, controlled reentry, and graveyard orbits, aim to mitigate space debris but have varying environmental implications that remain insufficiently explored. During reentry, up to 90% of satellites are vaporized,¹¹ releasing metals, resins, and other toxic substances into the atmosphere,⁷ contributing to acidification, climate change, and particulate matter formation. Graveyard orbits, while reducing short-term collision risks, exacerbate long-term orbital congestion, and fragmentation potential. This study addresses the current methodological gap in environmental assessments of satellite EoL scenarios by introducing a combined Life Cycle Assessment (LCA) framework that integrates the Environmental Footprint 3.1 method with a dedicated Space Debris Indicator (SDI), enabling the evaluation of both terrestrial and orbital impacts. This combined framework evaluates environmental trade-offs across terrestrial, atmospheric, and orbital environments, providing an integrated view of satellite EoL impacts. Using a CubeSat as a case study, results indicate that controlled reentry has a higher environmental burden than natural reentry across multiple impact categories, not only due to fuel combustion but also because of a higher percentage of material ablation.¹³ While natural reentry generates relatively lower atmospheric emissions, it results in a larger mass of surviving fragments. However, these fragments contribute minimally to the overall environmental impact compared to the emissions from atmospheric ablation. In contrast, graveyard orbits eliminate atmospheric emissions entirely but represent the most significant challenge for long-term orbital sustainability, with the highest Space Debris Index, underscoring their lasting impact on orbital congestion and fragmentation risks. These findings underscore the need for EoL strategies that balance short-term environmental impacts with long-term orbital sustainability. Exploring circular economy principles and innovative materials, such as wood-based structures to mitigate aluminum oxide pollution, presents promising pathways. Additionally, enhancing on-orbit operations through maintenance, repair, and upgrading would extend satellite lifespans, possibly reduce new launches and support orbital sustainability goals.

1. Introduction

The rapid increase in satellite deployments for applications such as Earth observation, telecommunications, navigation, and other services has significantly expanded the use of Low Earth Orbit (LEO). However, this growing orbital activity raises concerns about long-term sustainability, particularly due to increased risks of collision events and potential loss of access to critical orbital regions. The prevailing "launch-use-discard" paradigm² has led to an accumulation of non-functional objects in orbit, with many satellites reaching End-of-Life (EoL) without proper disposal. This contributes not only to orbital congestion but also to the potential triggering of a collision cascade known as the Kessler Syndrome,¹⁰ a scenario in which space debris collisions generate more fragments, increasing the likelihood of further collisions and potentially rendering certain orbits unusable.

As orbital sustainability becomes increasingly threatened by congestion and cascading collision risks, it is essential to evaluate the environmental implications of satellite EoL strategies. These typically fall into three categories: uncontrolled natural reentry, controlled reentry using onboard propulsion, or relocation to graveyard orbits. Each of these Post-Mission Disposal (PMD) strategies involves distinct environmental trade-offs. While reentry options mitigate the growth of orbital debris, they may release high-temperature emissions whose long-term effects on the upper atmosphere

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remain poorly understood.⁸ Conversely, graveyard orbits avoid atmospheric reentry and therefore prevent the release of combustion by-products into the upper atmosphere, but increase long-term orbital occupation.

To address the environmental trade-offs of EoL strategies, Life Cycle Assessment (LCA) provides a structured method to quantify the environmental impacts of products or systems across their entire lifespan. As defined in the ISO 14040/44 standards,⁴ LCA involves four main phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. Although traditionally applied in terrestrial contexts, such as energy systems or the built environment, LCA is now being extended to the space sector to support more sustainable design and policy decisions. In parallel with the rising attention to orbital sustainability, recent studies have highlighted the need to adapt LCA methods to the specificities of space activities, such as the absence of direct emissions in space, the long-term persistence of orbital debris, and the unique challenges of EoL management beyond Earth's atmosphere.¹¹ Traditional LCA approaches tend to focus on terrestrial and atmospheric emissions, often overlooking orbital impacts. New metrics, such as the Space Debris Indicator (SDI), developed by Colombo et al.,³ now allow orbital externalities to be included in life cycle thinking.

Building on these recent methodological developments, this study applies the LCA methodology to assess and compare the environmental impacts of three EoL scenarios for a small satellite in LEO. By combining conventional midpoint indicators from the Environmental Footprint 3.1 (EF 3.1) method with the SDI, the analysis aims to capture the multi-domain nature of disposal impacts (orbital, atmospheric, and terrestrial). Conducted within the DLR internal project Impulsprojekt Orbitale Nachhaltigkeit (ION), this work provides insights that can support more environmentally informed satellite disposal strategies.

2. Methods

2.1 Goal and Scope Definition

The goal of this study is to evaluate and compare the environmental impacts associated with the EoL management of small satellites. The scope of the study includes three PMD scenarios commonly considered in LEO:

1. Natural reentry, in which the satellite passively decays and disintegrates as it reenters Earth's atmosphere
2. Controlled reentry, involving a maneuver with onboard propulsion to guide the satellite to a predefined point
3. Graveyard orbit, where the satellite is relocated to a higher, non-operational region to reduce collision risks

The objective is to quantify the environmental trade-offs of these scenarios by assessing their respective impacts across three domains. First, in the orbital environment, the study examines the persistence of inactive objects, the risks of collisions or fragmentation, and the long-term occupation of orbital regions. Second, in the atmosphere, it considers emissions produced by onboard propulsion systems and by the high-temperature disintegration of satellite components during reentry. Finally, in the terrestrial environment, the analysis includes potential impacts from surviving debris fragments that may reach Earth's surface, particularly in oceanic areas where reentry is typically directed.

The work is carried out as part of the ION project, which aims to advance the sustainability of orbital operations by promoting circularity and responsible disposal practices. The results are intended to support the development of EoL strategies that minimize environmental burdens across all three domains. The functional unit of this study is defined as the PMD of one 3U CubeSat (5 kg) initially deployed in LEO.

The selected EoL scenarios align with the topology used in previous LCA-based space sustainability studies, such as Maury et al.,¹¹ which also consider controlled reentry and natural orbital decay.

2.2 System Description and Scenarios

The system analyzed in this study is a 3U CubeSat designed for missions in LEO. The satellite has dimensions of 10 x 10 x 30 cm and a launch mass of 5 kg. It includes several key subsystems: a structural frame made of aluminium alloy (e.g., 6061-T6), solar panels composed of photovoltaic cells and protective glass, electronic units including avionics, onboard processing and communications, lithium-ion batteries for energy storage, multilayer insulation for thermal control, and a propulsion system, which is only present in scenarios that involve active orbital maneuvers. A detailed breakdown of materials and masses is presented in Table 1.

The system boundaries are limited to the EoL phase and follow a gate-to-gate approach, meaning that only the processes occurring during the PMD phase are considered, from the start of EoL operations to the final disposal outcome. Upstream processes (e.g., manufacturing or launch) are excluded for this assessment. In the first scenario (i.e., natural reentry) the satellite is left to decay passively due to atmospheric drag, leading to an uncontrolled reentry and partial disintegration in the upper atmosphere. In the controlled reentry scenario, an active deorbit maneuver is performed

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Table 1: Breakdown of CubeSat components, materials and masses.

Component	Material	Mass (%)	Mass (kg)
Structure	Aluminium alloy (e.g., 6061-T6)	60	3.00
Solar Panels	Silicon and tempered glass	10	0.50
Electronics	PCB, copper and connectors	20	1.00
Batteries	Lithium-ion cells	10	0.50
Thermal Subsystem	MLI (Kapton, Mylar layers)	1-5	0.25
Propulsion Unit	Hydrazine thruster or cold gas	5	0.25

Note: The propulsion unit is only included for scenarios involving active maneuvers

using onboard propulsion, enabling a targeted reentry through a predefined atmospheric corridor. This allows for optimized trajectory and orientation, resulting in stronger thermal loads and consequently near-complete disintegration, in contrast to the more uncertain and often partial disintegration observed in natural reentries. The third scenario, the graveyard orbit, involves a maneuver to transfer the satellite to a higher, stable orbit beyond the operational LEO region, where it remains indefinitely. Although no atmospheric reentry occurs in this case, the environmental impacts associated with the production of the required propellant are included, based on available Life Cycle Inventory (LCI) data from the European Space Agency (ESA) LCA database. This includes upstream impacts from raw material extraction, chemical synthesis, infrastructure, and standard transportation assumptions up to the production plant gate.

As mentioned in section 2.1, environmental impacts are analyzed across three domains, each affected differently depending on the scenario. The orbital environment is impacted by long-term debris presence and congestion, particularly in the case of graveyard orbits. The atmosphere is affected by emissions arising from propulsion systems and the disintegration of materials during reentry. The terrestrial environment may be affected by surviving fragments reaching the Earth's surface, especially in marine regions where reentry is typically directed. Table 2 provides an overview of how each EoL scenario contributes to environmental impacts across the terrestrial, atmospheric, and orbital domains.

Table 2: Environments impacted by each end-of-life scenario.

	Natural Reentry	Controlled Reentry	Graveyard Orbit
Terrestrial	✓	–	✓
Atmospheric	✓	✓	✓
Orbital	✓	–	✓

Note: ✓: impact present, – : no significant impact

Each scenario leads to specific types of environmental impacts. Atmospheric effects are mainly linked to the combustion of fuel and the ablation of satellite materials, releasing gases such as carbon dioxide (CO₂) and fine particles like aluminium oxides (Al₂O₃), and particulate matter with a diameter of less than 2.5 micrometers (PM_{2.5}). Some of these particles may eventually settle on terrestrial ecosystems. Terrestrial impacts arise from components that do not fully disintegrate during reentry and may reach the ground, with the assumption in this study that such fragments fall into marine environments. Orbital impacts are associated with the long-term presence of non-operational objects, which may increase the risk of collisions and contribute to the congestion of valuable orbital regions. Table 3 summarizes how these impact mechanisms are distributed across the three environmental domains.

Table 3: Overview of environmental impacts by domain.

	Terrestrial	Atmospheric	Orbital
Long term orbital occupation and fragmentation risk	–	–	✓
Fuel consumption	–	✓	–
Fuel production	✓	✓	–
Emissions from satellite demise	✓	✓	–
Fragments reaching Earth	✓	✓	–

Note: ✓: impact present, – : no significant impact

In scenarios involving propulsion, namely controlled reentry and graveyard orbit, the amount of fuel required is estimated using the Tsiolkovsky rocket equation.¹¹ The environmental impacts associated with the production of this propellant are included in the LCI.

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2.3 Life Cycle Inventories

The LCI phase gathers and quantifies all relevant input and output flows associated with the PMD scenario. In this study, inventories include atmospheric emissions generated during reentry, production and use of propellants in active disposal scenarios, and the possible fate of surviving debris ending up in the marine environment, although this is not modeled in the present study.

The LCI data were compiled using a combination of scientific literature, chemical reaction modeling and stoichiometric decomposition assumptions based on satellite material decomposition. Each modeled emission was matched to a corresponding elementary flow, that is, a substance directly exchanged between the technosphere and the environment, as listed in either the ecoinvent 3.9.1 cut-off database¹⁴ or the ESA LCA database.⁵ All calculations and model implementations were carried out using the open-source LCA framework Brightway2.

To simulate material decomposition during atmospheric reentry, chemical reactions were identified for each major material group (e.g., aluminium, silicon, copper, lithium) and the corresponding emissions were estimated. The expected burn-up efficiency was set to 80% for natural reentry and 99% for controlled reentry.¹² Surviving material fragments from incomplete burn-up were assumed to fall into oceanic regions in line with standard reentry protocols.

For active scenarios involving propulsion, the consumption of hydrazine fuel was estimated using the Tsiolkovsky rocket equation, assuming a delta-v of 100 m/s for controlled reentry and 50 m/s for transfer to graveyard orbit, in line with the values used by Maury et al.¹¹ This estimates reflect typical LEO maneuvers for small satellites and are sufficiently accurate for scenario comparison in this study. This yielded a total propellant mass of 226.4 g and 114.5 g, respectively, for a 5 kg CubeSat. The environmental impacts of hydrazine production are included using the process from the ESA LCA database. Combustion emissions from hydrazine (CO₂, H₂O and NO_x) were also included for the controlled reentry scenario.

Aluminium oxides released during atmospheric ablation were approximated using fine particulate matter emissions in the upper atmosphere, serving as a proxy due to the lack of alumina specific flows. This assumption reflects the formation of submicron alumina particles under high-temperature reentry conditions. Similarly, emissions of volatile organics (e.g., from battery electrolytes or polymers) were approximated using non-methane volatile organic compound flows.

A complete material breakdown by component, as presented in Table 1, was used to attribute emission types and quantities to each material group. Table 4 summarizes the chemical decomposition pathways and resulting emission products assumed for each CubeSat component during reentry. The total mass of disintegrated materials was capped to match the disintegration percentage for each scenario (4.68 kg for natural reentry, 4.95 kg for controlled reentry). Surviving fragments were modelled as emissions to the marine environment.

Table 4: Material decomposition pathways and emission products during reentry.

Component	Material	Decomposition	End Product
Structure	Aluminum	Vaporization and oxidation	Aluminum oxides
Solar Panels	Silicon	Oxidation at high temperature	Silicon oxides
Solar Panels	Glass (SiO ₂)	No decomposition	Glass fragments
Solar Panels	Aluminum	Vaporization and oxidation	Aluminum oxides
Electronics	Copper	Surface oxidation	Copper oxides
Electronics	Gold	No decomposition	No transformation
Electronics	Lead	Oxidation in upper atmosphere	Lead oxides
Batteries	Lithium	Rapid oxidation	Lithium oxides
Batteries	Cobalt	Oxidation in air	Cobalt oxides
Batteries	Nickel	Oxidation in air	Nickel oxides
Batteries	Manganese	Oxidation in air	Manganese oxides
Batteries	Organic electrolyte	Thermal degradation	Gaseous emissions (CO ₂ , HF, etc.)
Thermal Subsystem	Kapton (polyimide)	Thermal degradation	VOCs + carbon residue
Propulsion Unit	Hydrazine	Combustion during reentry	Nitrogen, water vapor, NO _x
Propulsion Unit	Aluminum tank	Vaporization and oxidation	Aluminum oxides

The residence time in orbit was defined for each PMD scenario to support the calculation of orbital impacts using the SDI. A duration of 1 year was assumed for controlled reentry, representing a short orbital presence following the deorbit maneuver, as also considered in Maury et al.¹¹ For natural reentry, a residence time of 5 years was selected, reflecting a typical passive decay duration for a 3U Cubesat in LEO at an altitude of 550 km. For the graveyard orbit scenario, a duration of 1000 years³ was adopted to represent long-term occupation of a stable, non-decaying orbit beyond the

operational region.

2.4 Life Cycle Impact Assessment

The study adopts a dual-method approach to quantify the environmental impacts associated with each PMD scenario. Impacts on the terrestrial and atmospheric domains are assessed using the EF 3.1¹ methodology, while a complementary indicator, adapted from Colombo et al.,³ is applied to evaluate impacts on the orbital environment.

2.4.1 Environmental Footprint 3.1 Methodology

The environmental impacts are assessed using the EF 3.1 methodology, which includes a set of midpoint indicators. These indicators represent impacts at an intermediate stage in the cause-effect chain, such as climate change potential or acidification, and are relevant to atmospheric and terrestrial effects. Table 5 lists the five selected impact categories used in this study, along with their respective indicators and units.

Table 5: Impact categories and indicators used in this study (EF 3.1).

Impact Category	Indicator	Unit
Climate Change	Global Warming Potential	kg CO ₂ -eq
Acidification	Accumulated Exceedance	mol H ⁺ -eq
Ecotoxicity, Freshwater	Comparative Toxic Unit for ecosystems	CTUe
Eutrophication, Marine	Nutrients reaching marine end compartment (P)	kg N-eq
Particulate Matter	Impact on human health	disease incidence

These categories were selected based on their relevance to the physical processes modeled in the EoL scenarios: fuel combustion during orbital maneuvers, release of toxic materials during ablation, and surviving fragments reaching the Earth. Acidification captures the potential for acid-forming substances, such as nitrogen and sulfur oxides, to impact terrestrial and aquatic ecosystems.⁶ Climate change accounts for the radiative forcing effects of greenhouse gases released primarily during propulsion and material ablation.⁶ Freshwater ecotoxicity reflects the toxicological stress on aquatic life from substances like metals and combustion residues that may eventually deposit into freshwater bodies.⁶ Marine eutrophication considers the release of nitrogen-based compounds that can contribute to nutrient enrichment in marine environments, especially from surviving fragments entering oceanic areas.⁶ Finally, the particulate matter indicator estimates the incidence of human health effects caused by fine particles, including aluminium oxides and PM_{2.5}, emitted during high-temperature reentry disintegration.⁶

2.4.2 Space Debris Indicator

Traditional Life Cycle Impact Assessment (LCIA) methodologies, such as the EF 3.1, provide comprehensive coverage of terrestrial and atmospheric impacts but lack any quantification of the environmental burdens specific to the orbital environment. To address this gap, this study incorporates the SDI developed by Colombo et al.,³ which enables the assessment of long-term impacts resulting from PMD strategies on orbital sustainability.

The SDI quantifies the environmental footprint of an object left in orbit by combining three key dimensions: (1) the occupation of orbital resources, (2) the risk of fragmentation due to collision or explosion, and (3) the potential human casualty risk from uncontrolled reentry. These three components are combined into a single overall indicator:

$$I_{\text{debris}} = n_{\text{resource}} \cdot w_{\text{resource}} \cdot I_{\text{resource}} + n_{\text{risk}} \cdot w_{\text{risk}} \cdot I_{\text{risk}} + n_{\text{casualty}} \cdot w_{\text{casualty}} \cdot I_{\text{casualty}} \quad (1)$$

where I_{resource} represents orbital resource use, I_{risk} the propagation risks associated with collision or explosion, and I_{casualty} the risk for human life. The parameters n_i and w_i correspond respectively to normalization and weighting factors. In the present study, I_{casualty} is excluded to prevent double counting, as the potential health impacts from surviving fragments (e.g., ground casualties or toxic emissions) are already accounted for within the five selected EF 3.1 impact categories.

The resulting orbital impact indicator becomes:

$$I_{\text{debris}} = n_{\text{resource}} \cdot w_{\text{resource}} \cdot I_{\text{resource}} + n_{\text{risk}} \cdot w_{\text{risk}} \cdot I_{\text{risk}} \quad (2)$$

Each component is computed using well-defined models and orbital parameters. The specific implementation for the CubeSat studied here is described below.

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Implementation in this study. The SDI is implemented using satellite-specific parameters from the 3U CubeSat, including its mass (5 kg), estimated cross-sectional area (approximately 0.03 m²), and the residence time associated with each EoL scenario. Collision probabilities are calculated using the simplified kinetic gas model proposed by Colombo et al.,³ assuming typical values for LEO: an object density of around 10⁻⁹ objects per cubic meter and a mean relative velocity of 10 km/s. The severity of collision or explosion events is estimated using a power law based on the satellite's mass.³ In this model, severity scales with the object's mass raised to an exponent (0.75), reflecting the non-linear relationship between satellite mass and the amount of debris generated. To remain consistent with the original methodology, but within the limits of available tools, this study uses a simplified integration approach instead of full orbital propagation. Specifically, the occupation of orbital space is modeled by approximating average orbital density and multiplying it by the estimated time the satellite remains in orbit. While Colombo et al.³ propose a more detailed time-integrated function based on evolving orbital elements, this level of detail typically requires software such as DRAMA, which is not used in the present study. Explosion probabilities are assumed to be low but non-zero, based on observed historical rates. Normalization and weighting factors are kept consistent across scenarios to allow direct comparison. By applying this adapted version of the SDI framework, the orbital impacts of each disposal scenario can be systematically compared and integrated with terrestrial and atmospheric assessments for a comprehensive life cycle evaluation.

Orbital Resource Use (I_{resource}). This term quantifies the long-term occupation of valuable orbital regions, particularly in congested zones such as LEO. It is proportional to both the time Δt an object remains in orbit and the local spatial density ρ of orbital objects:

$$I_{\text{resource}} \propto \int_{t_0}^{t_f} \rho(t) dt \quad (3)$$

In this study, ρ is approximated by average values for typical LEO altitudes and Δt corresponds to the residence time of the CubeSat under each EoL scenario:

- For natural reentry: time until atmospheric drag causes decay
- For controlled reentry: short residence due to immediate deorbit maneuver
- For graveyard orbit: indefinite presence beyond the operational LEO region

Propagation Risk (I_{risk}). The risk of debris proliferation from a given object is assessed through the combination of collision and explosion scenarios:

$$I_{\text{risk}} = p_c \cdot e_c + p_e \cdot e_e \quad (4)$$

where p_c and p_e are the probabilities of collision and explosion, and e_c , e_e represent the severity of these events in terms of their impact on the space environment.

The collision probability p_c is derived using a kinetic gas model:³

$$p_c = 1 - \exp(-\rho \cdot \Delta v \cdot A \cdot \Delta t) \quad (5)$$

Here, ρ is again the spatial density of potential impactors, Δv is the average relative velocity between objects (typically assumed as 10 km/s in LEO, A is the cross-sectional area of the object, and Δt the duration of exposure. The severity term e_c is modeled based on the expected increase in collision probability caused by the resulting fragment cloud. It follows a scaling law with the object mass:

$$e_c \propto \left(\frac{m}{10,000 \text{ kg}} \right)^{0.75} \quad (6)$$

A similar relationship is applied for e_e , with p_e typically taken as a small value derived from historical failure rates (e.g., spontaneous battery explosions). In the case of a 5 kg CubeSat, both e_c and e_e are significantly lower than for large satellites but remain non-zero.

3. Results

3.1 EF3.1 Impact Results

Figure 1 illustrates the comparison between the relative environmental impacts of the three EoL scenarios, controlled reentry, natural reentry, and graveyard orbit, across the five selected EF 3.1 impact categories. Each category is normalized individually, with the natural reentry scenario set as the reference (100%). Controlled reentry consistently shows higher impacts than natural reentry, with particularly elevated values for acidification and marine eutrophication. In contrast, the graveyard orbit scenario results in significantly lower impacts for all categories.

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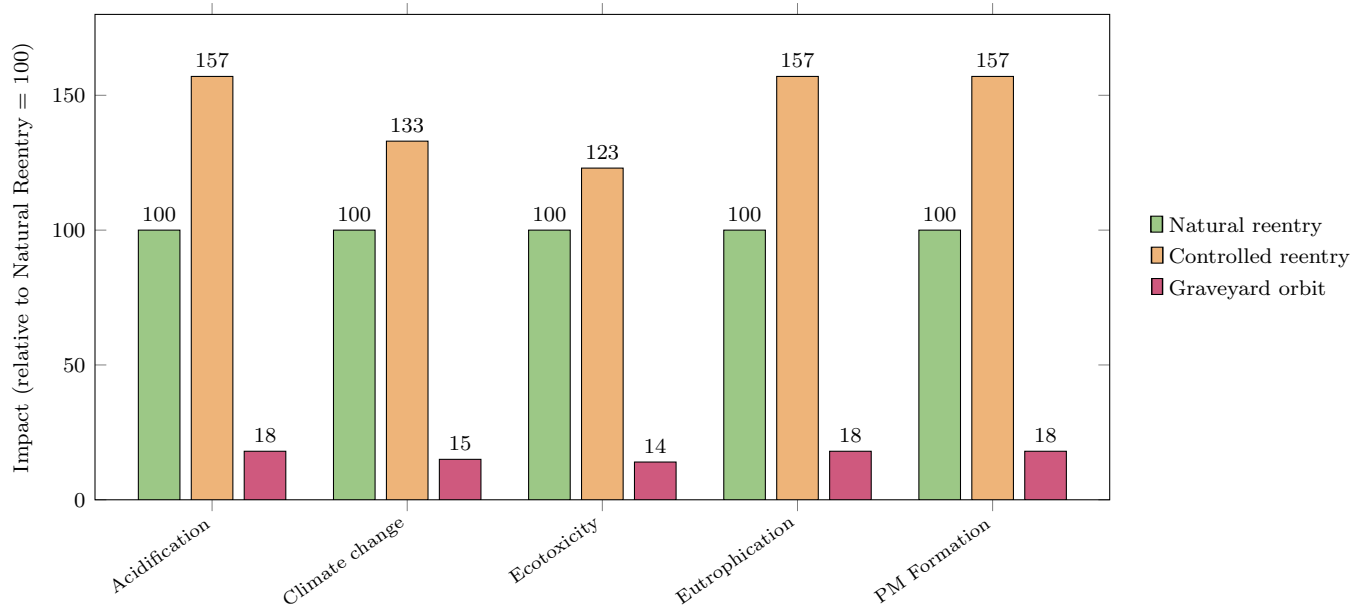


Figure 1: Comparison of end-of-life scenarios based on EF3.1 impact categories.

Figure 2 presents the contribution of individual emission sources and subsystems modeled within the controlled reentry scenario to the total environmental impacts. Ground-based fuel production is the dominant contributor to climate change (accounting for over 96% of total CO₂-eq emissions) and also significantly impacts freshwater ecotoxicity and particulate matter formation. Atmospheric disintegration, driven by the high-temperature ablation of onboard materials, is the main contributor to acidification and marine eutrophication. Fuel consumption, although smaller in magnitude, still contributes to acidification and eutrophication. The contribution from surviving fragments is negligible in all categories due to the high assumed burn-up efficiency (99%). This breakdown allows for the identification of the most impactful mechanisms during controlled reentry and highlights the environmental trade-offs associated with propulsion-enabled disposal.

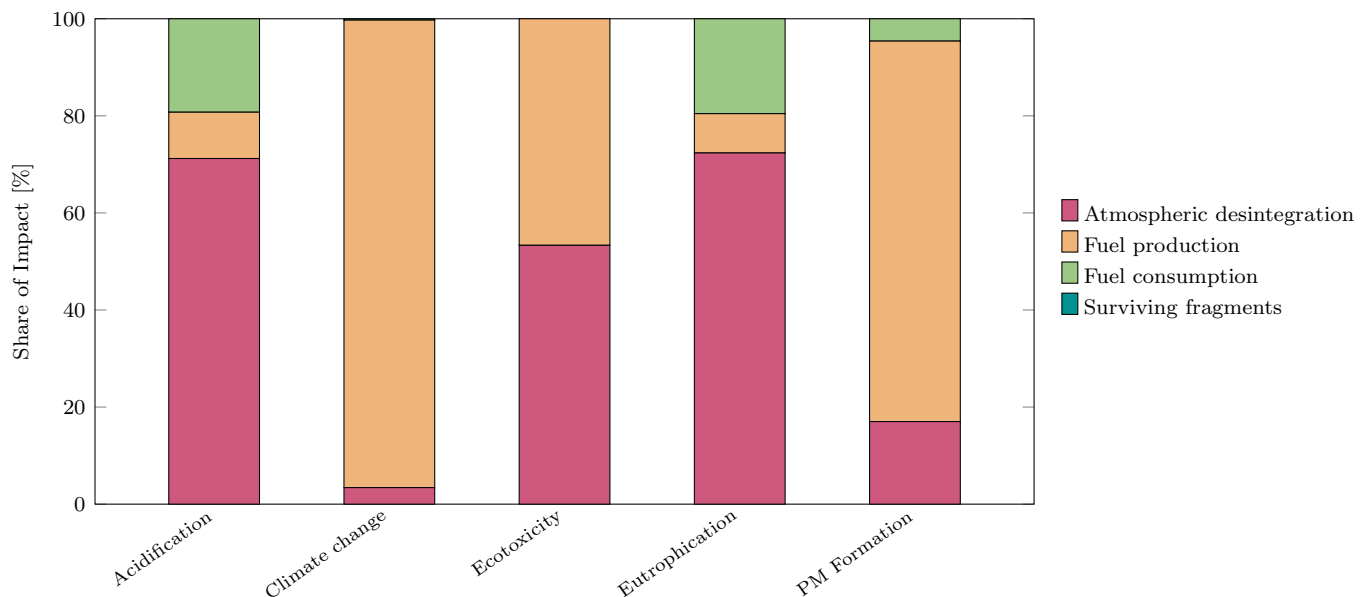


Figure 2: Relative contribution of disposal phases to controlled reentry impacts (EF3.1).

Table 6 highlights the primary contributors to each impact category during atmospheric reentry. Since material decomposition depends on the mass share and material makeup of each component, the results apply to any scenario involv-

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ing the atmosphere, regardless of the specific burn-up efficiency. The propulsion system and structural frame dominate acidification and marine eutrophication impacts. Climate change impact is mainly associated with the aluminium-based structure. Freshwater ecotoxicity is overwhelmingly driven by the batteries, followed by minor contributions from electronics and thermal insulation. Particulate matter emissions mainly originate from batteries and, to a lesser extent, from the structural frame and solar panels. The remaining percentages correspond to minor contributions from other subsystems, such as electronics, thermal insulation, or structural elements with negligible effects.

Table 6: Main contributing components per EF3.1 impact category (controlled and uncontrolled reentry scenarios).

Impact Category	Main Contributing Components
Acidification	Propulsion system (63.4%), Structure (32.0%)
Climate Change	Structure (92.5%)
Freshwater Ecotoxicity	Batteries (99.8%)
Marine Eutrophication	Propulsion system (52.3%), Structure (26.4%)
Particulate Matter Formation	Solar panels (44.6%), Batteries (35.8%)

3.2 Orbital Impact Results

Table 7 presents the results of the SDI for each scenario. The graveyard scenario yields the highest overall SDI value, primarily due to its long-term occupation of orbital space. Natural reentry results in moderate orbital impact, while controlled reentry, which minimizes time spent in orbit, has the lowest SDI.

Table 7: Space Debris Indicator values for each end-of-life scenario.

Scenario	I_{resource}	I_{risk}	SDI (sum)
Controlled Reentry	2.59E-4	3.38E-5	2.93E-4
Natural Reentry	0.158	0.01392	0.1719
Graveyard Orbit	31.5	0.01802	31.518

4. Discussion

4.1 Interpretation of Results

The results highlight the existence of clear trade-offs between terrestrial/atmospheric impacts and those related to the orbital environment. While controlled reentry emerges as the most favorable strategy in terms of orbital sustainability, reflected by the lowest SDI value, it also incurs the highest environmental burden in all EF 3.1 categories, particularly in terms of acidification and marine eutrophication. This is largely driven by the upstream impacts of propellant production and the emissions resulting from high-temperature disintegration of satellite materials. By contrast, natural reentry results in lower terrestrial and atmospheric impacts but maintains a non-negligible orbital footprint due to the prolonged residence time prior to decay. Graveyard orbit, although favorable from an atmospheric perspective, owing to the absence of reentry and associated emissions, leads to a disproportionately high orbital impact, primarily caused by the indefinite occupation of valuable orbital resources. As more objects accumulate in graveyard orbits, their long-term saturation could further limit disposal options and increase orbital congestion. Interestingly, the analysis shows that the environmental contribution of surviving fragments is negligible across all EF 3.1 categories. This observation suggests that maximizing burn-up efficiency may not necessarily be beneficial from an environmental perspective. Since atmospheric disintegration accounts for the bulk of the terrestrial and atmospheric impacts, reducing the proportion of materials ablated during reentry could lower the overall environmental burden. In that regard, a lower burn-up rate might be preferable, provided that surviving fragments are reliably directed toward controlled and uninhabited areas, such as oceanic reentry corridors. However, this raises additional considerations regarding public safety and casualty risk, emphasizing the importance of precise targeting in disposal operations. These findings confirm that no single EoL strategy is environmentally superior across all dimensions. Rather, each scenario exhibits specific strengths and weaknesses depending on the domain under consideration. While this study aligns with key insights from Colombo et al.³ and Maury et al.,¹¹ it extends previous work by integrating the assessment of all three affected environments within a comparative LCA of multiple EoL scenarios for a CubeSat. Based on this analysis, it is suggested

that a responsible selection of PMD strategies must consider not only terrestrial and atmospheric consequences, as traditionally done in LCA studies, but also the long-term sustainability of the orbital environment. Controlled reentry appears to offer the best compromise when aiming to minimize the space debris especially for densely populated orbits such as LEO. However, this strategy entails a significant increase in fuel-related impacts, raising questions about the environmental cost of compliance with debris mitigation guidelines such as the 25 year rule for PMD in LEO.⁹ As shown in Figure 2, over 96% of the impact on climate change in this scenario stem from propellant production. This calls for greater attention of propulsion system design and suggests that alternative low-impact propellants or disposal-assist mechanisms may provide more sustainable options. For missions with limited propulsion capability or marginal mass budgets, natural reentry may still be a viable option, offering a moderate orbital impact profile while avoiding the upstream burdens of propellant use. In contrast, the graveyard orbit scenario should be approached with caution, as its long-term occupation of orbital space could undermine broader space sustainability efforts, even if terrestrial emissions are minimized. While this study focuses on a low-mass CubeSat in LEO, it is worth noting that larger spacecraft, such as satellites or massive platforms like ENVironment SATellite (ENVISAT), may follow different EoL strategies, including active deorbiting using electric propulsion. However, these cases involve distinct technical and energetic considerations and fall beyond the scope of this analysis.

4.2 Limitations and Future Work

Several methodological assumptions and simplifications were necessary in this study, which introduce limitations that should be acknowledged. First, the estimation of orbital residence times relies on fixed durations (3, 5 and 1000 years for controlled, natural, and graveyard scenarios, respectively), without accounting for variations in altitude, inclination or drag effects. The absence of a propagation tool such as DRAMA³ restricts the precision of the SDI implementation, particularly for modeling evolving orbital dynamics. Second, numerous approximations were required to model atmospheric disintegration. Neitherecoinvent nor the ESA LCA database currently provide emission profiles corresponding to the high-temperature decomposition of spacecraft materials. Consequently, this study relied on proxies, most notably PM_{2.5} emissions, to approximate products and particulate release, especially for aluminium oxides (Al₂O₃). However, as shown in recent research,^{7,12} the chemical behavior and potential ozone depleting effects of alumina nanoparticles remain poorly understood and likely underrepresented in conventional LCA approaches. Additionally, the vertical stratification of the atmosphere was not considered. Indeed, emissions were treated uniformly, although the environmental impact of particles and gases varies significantly depending on the atmospheric layer in which they are released. Third, the current system boundary excludes the potential influence of additional fuel mass during launch. Additionally, potential design variations across EoL scenarios were not considered. For instance, satellites intended for controlled reentry might feature more modular structures or different material choices to optimize disintegration, whereas those destined for graveyard orbits may prioritize compactness or structural robustness. This is particularly relevant for scenarios involving propulsion (controlled reentry and graveyard orbit), which would require heavier launch configurations and thus potentially increase upstream impacts. Moreover, the analysis does not include ground-based operations recovery logistics.

Regarding the SDI, while the adapted version from Colombo et al.³ provides a valuable entry point for integrating orbital externalities, it simplifies collision risk using average density values and assumes constant relative velocity. Alternative orbital impact metrics, such as those based on fragment propagation models or long-term congestion indices, could complement or refine these results in future work.

Future research should prioritize the development of improved decomposition models that can distinguish emissions by material type and by atmospheric layer. Such refinement is essential for more accurately capturing the environmental consequences of high-temperature disintegration, especially as the reentry altitude influences the residence time and chemical fate of emitted particles and gases. In particular, the formation and behavior of aluminium oxides (Al₂O₃) in the mesosphere and stratosphere, as highlighted by Ferreira et al.,⁷ warrant further investigation due to their potential to impact ozone chemistry. In parallel, future studies should explore the comparative impacts of reentry using alternative satellite materials, particularly low-emission or bio-based alternatives (e.g., wood-based structures), which could reduce the burden of ablation products. Finally, while the present study focuses exclusively on the disposal phase, extending the system boundaries to include the full cradle-to-grave life cycle would enable a more comprehensive evaluation of satellite EoL strategies. Although such an extension would not alter the direct impacts of the disposal phase itself, it would provide important contextual insights, helping to identify potential trade-offs and burden-shifting across the mission lifecycle. Moreover, the inclusion of emerging technologies such as active debris removal, which refers to the targeted removal of non-functional satellites or debris from orbit, could influence EoL impacts. These approaches incur additional environmental burdens during deployment and operation but may substantially reduce long-term orbital occupation and fragmentation risks, potentially reshaping the overall sustainability profile of EoL strategies. Similarly, on-orbit servicing, including inspection, maintenance, refueling, or upgrading of satellites, may

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extend mission lifetimes and defer disposal, thereby mitigating the frequency of satellite replacement and reducing cumulative launch- and disposal-related impacts over time.

5. Conclusion

This study presented a comparative environmental assessment of three EoL scenarios for small satellites in LEO: natural reentry, controlled reentry using onboard propulsion and transfer to a graveyard orbit. By combining the EF 3.1 method with the SDI, the analysis provides a multidimensional perspective on the trade-offs between orbital sustainability and terrestrial/atmospheric environmental burdens.

The results highlight a fundamental tension between minimizing orbital congestion and limiting atmospheric and terrestrial emissions. Controlled reentry yields the lowest orbital impact, as reflected by its minimal SDI value, but comes at a high environmental cost due to propellant production and high-temperature disintegration of materials. Graveyard orbit minimizes terrestrial emissions but imposes a disproportionately high burden on orbital sustainability due to indefinite resource occupation. For satellites in LEO, natural reentry offers a compromise: moderate impacts across all domains, with the benefit of requiring no active propulsion.

Interestingly, under the assumption of 99% destruction during atmospheric reentry, the analysis reveals that surviving fragments contribute negligibly to the modeled environmental impacts, which include global-scale terrestrial impacts but exclude localized damage or human safety risks. This suggests that maximizing burn-up efficiency may not always be desirable from a terrestrial perspective. Instead, controlled targeting of surviving debris to uninhabited oceanic zones could offer a more balanced approach.

These findings underscore the importance of adopting a system-level perspective when selecting EoL strategies. Rather than seeking a universally optimal solution, mission planners should weigh domain-specific impacts according to the mission profile, regulatory context and available resources. The incorporation of orbital sustainability metrics such as the SDI into LCA frameworks represents a crucial step toward this integrated assessment.

Looking forward, improvements in material decomposition models, finer atmospheric emissions data and the integration of low-impact propulsion systems, including passive and active deorbiting technologies like drag sails, electrodynamic tethers and electric propulsion, will enhance the accuracy and sustainability of future EoL scenarios.

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