De-TECH Tech Challenge 2025 - Aerospace Edition

BIODEMIS - A Biologically Produced Cellulose-Chitin Composite for Sustainable Satellite Structures and Design for Demise

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1. Motivation and Challenge Context

The rapid increase in satellite launches and the construction of large-scale megaconstellations have intensified the debate on sustainability in space technology. In 2019, roughly 5,000 satellites were in orbit [1]. By October 2024, the German newspaper *DIE ZEIT* reported that this number had risen to about 13,200, including 6,000 satellites from SpaceX’s Starlink constellation [2]. Just one year later, in August 2025, the number of Starlink satellites alone increased by more than 50 % to 9,377 [3]. SpaceX ultimately aims to establish a megaconstellation of around 34,000 satellites.

At the same time, other spacefaring nations such as China are pursuing similar ambitions. Projects like Qianfan and GW plan to deploy constellations of approximately 15,000 and 13,000 satellites respectively [2]. The operational lifespan of most satellites in these constellations does not exceed five years, which necessitates a reliable and controlled disposal process.

Most satellites are constructed from aluminum alloys, which offer a combination of low density and high mechanical strength. However, their production is highly energy-intensive and relies on bauxite mining and large-scale electrolysis facilities. At the end of their life cycle, satellites typically reenter the atmosphere and burn up. During this process, aluminum is oxidized to alumina particles that disperse into the upper atmosphere. With the rapid expansion of satellite constellations, several tons of aluminum are expected to enter and burn in the atmosphere each year. Researchers estimate that by 2040 12,000 satellites will be disposed of annually, emitting respectively 10,000 tons of aluminium oxide [4].

The implications of satellite disposal are threefold:

1. **Loss of resources**: The valuable materials used in satellite manufacturing are irretrievably lost during atmospheric burn-up.

2. **Space debris**: Failed or uncontrolled deorbiting increases the risk of collisions and threatens the safety of future space operations.

3. **Environmental uncertainties**: The long term effects of aluminum and alumina nanoparticles on the ozone layer, weather systems and Earth's radiative balance remain insufficiently understood but are an increasing environmental concern.

The De-TECH Challenge calls for new materials that can replace aluminium at least in part and support controlled burn-up behaviour. The aim is to design materials that are stable during operation but oxidize completely on reentry, leaving no persistent debris. The project BIODEMIS proposes a biologically produced cellulose-chitin composite that can be grown from renewable or waste-based resources. This material combines the mechanical properties of bacterial cellulose with the controlled degradability of chitin and offers a sustainable alternative for secondary satellite structures.

2. Biological Basis and Material Properties

BIODEMIS builds on the natural ability of the bacterium *Komagataeibacter xylinus* to produce highly pure bacterial cellulose. The taxonomy and metabolic characteristics of this species are well established [5]. The biosynthetic machinery responsible for cellulose formation has been described in detail and allows genetic modification to expand its product spectrum [6]. Under aerobic conditions, *K. xylinus* converts glucose into a dense nanofibrillar network that forms a strong hydrogel at the air liquid interface [7]. Studies have shown that bacterial cellulose can be produced efficiently on alternative low cost substrates such as corn steep liquor or fruit residues [8, 9], and strain optimization further increases the yield [10].

In BIODEMIS, the bacterial pathway is modified by introducing genes from *Saccharomyces cerevisiae* that increase the intracellular pool of UDP-N-acetylglucosamine [11]. This modification allows the cellulose synthase complex to co-polymerize both glucose and N-acetylglucosamine, forming a cellulose-chitin composite. The resulting material combines the stiffness and purity of cellulose with the functional groups of chitin, which improve flexibility and controlled degradability.

Chitin is a natural polymer found in fungi and arthropods and has been studied for its potential use as bioactive fibre [9, 10]. Enzymes such as lysozymes and chitinases can cleave chitin containing structures and thereby influence the degradation rates [14, 15, 16]. The combination of cellulose and chitin creates a tunable material: the cellulose provides mechanical integrity, while the chitin fraction allows enzymatic breakdown under defined conditions. The relationship between nitrogen availability in the growth medium and the chitin content in the final polymer enables process control over material stability and degradation speed [17].

Thermal analysis of cellulose-chitin composites shows decomposition between 250 and 320 °C [14, 15, 16]. This is well above typical temperature fluctuations in orbit but far below the several hundred degrees reached during atmospheric reentry. The material is therefore stable in operation yet burns completely in the reentry phase. Densities around 1.3 grams per cubic centimetre mean that BIODEMIS is about half as dense as aluminium, allowing significant mass savings in spacecraft design.

Toxicological studies on cellulose nanofibrils and related biopolymers demonstrate low toxicity and good biocompatibility [18, 19, 20]. This makes BIODEMIS a safe and environmentally compatible material not only for space applications but also for terrestrial use.

3. Production Concept and Resource Integration

The production concept of BIODEMIS links biological synthesis with circular resource use. On Earth, the bacterium can be cultivated in bioreactors using inexpensive substrates derived from agroindustrial side streams. Studies on bacterial cellulose production have already demonstrated that components such as corn steep liquor or molasses are suitable nutrient sources [8, 9]. Mutationbased selection and adaptive evolution have been used successfully to improve the cellulose yield [10]. Waste-to-resource processes of this kind are increasingly seen as a key step towards sustainable material production [21].

For long-term missions in space, the same principle can be applied in a closed-loop life-support system. Anaerobic waste treatment produces organic acids and sugars that can be used by *K. xylinus* as carbon sources [11]. The integration of biological waste processing with material production enables continuous recycling: waste is converted into new material for repair or maintenance. The process operates at around 30 °C and does not require light, which makes it compatible with spacecraft environments. In microgravity, film formation can be supported by centrifugal bioreactors or capillary-based interfaces that mimic the gravity-dependent surface behaviour observed on Earth.

After growth, the cellulose-chitin hydrogel is purified using mild acid treatment and carbon dioxide washing, both established steps in bacterial cellulose processing. The hydrogel can then be dried and pressed into thin sheets or laminates. These can be used directly as insulation or internal support panels or can serve as cores in sandwich structures with metallic or composite skins. For improved radiation resistance or moisture control, thin ceramic or graphene-based coatings can be applied.

4. Application and Performance Evaluation

BIODEMIS is intended for use in non-critical structural and interior components of satellites, where electrical insulation or low density is advantageous. Typical applications include interior panels, equipment supports, cable guides and protective casings. The material's mechanical strength in the range of tens to hundreds of megapascals [6, 17, 18] is sufficient for these roles, and its dielectric properties make it suitable for electronic housings.

Thermogravimetric analysis of related composites indicates that decomposition begins above 250 °C and accelerates near 300 °C [14, 15, 16]. During reentry, heating rates of several thousand degrees per second ensure that all organic components oxidize completely. Computational models of small satellite reentry suggest that even millimetre-thick BIODEMIS layers would fully combust above 70 kilometres altitude. This meets the design-for-demise criterion by ensuring that the material does not survive to ground impact or contribute to metallic particle formation.

Vacuum stability and outgassing behaviour could be verified through standard tests, and surface coatings can further reduce potential risks. The combination of experimental validation and numerical modelling will determine the operational window of the material and confirm its compatibility with satellite design standards.

5. Outlook and Relevance

BIODEMIS offers a promising approach to making spacecraft more sustainable. It provides a realistic and scalable alternative to conventional metals, helping to reduce emissions and energy demand during production and throughout a satellite's entire lifetime. By preventing the release of aluminium oxides during atmospheric reentry, BIODEMIS contributes to cleaner and safer space operations. Its biological production process is flexible and renewable, and it can operate both on Earth and in space using organic waste or other renewable sources as feedstock.

At the current stage, BIODEMIS is not intended to replace aluminium in the main load-bearing structures of satellites. However, it already performs well in non-critical components such as panels, casings and interior structures. These applications make it suitable for near-term use without requiring major design changes. With further research on fibre alignment, material reinforcement and surface coatings, the composite could become stronger and more thermally stable. Over time, this progress could make it possible to use BIODEMIS in larger structural parts and eventually replace aluminium more broadly.

A key advantage of BIODEMIS is its predictable behaviour during reentry. The cellulose-chitin composite remains stable in orbit but decomposes completely at temperatures above 250 degrees Celsius, ensuring full combustion as the spacecraft descends through the atmosphere. This controlled demise prevents the formation of persistent debris or metallic particles and supports a safer orbital environment.

Beyond its use in space, the same production system can be applied to make medical hydrogels, biodegradable coatings or functional fibres. This demonstrates how synthetic biology can connect aerospace technology with the bioeconomy and contribute to the development of materials that are both high-performing and environmentally responsible.

BIODEMIS shows that biotechnology can become an active part of engineering rather than a supporting discipline. It offers a realistic path towards replacing aluminium in the long term and towards developing spacecraft that are efficient, recyclable and designed to completely disintegrate during re-entry, contributing to a sustainable future for space exploration.

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