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A Review on Bio Composites for Sustainable Construction in Extraterrestrial Environment

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Abstract - This study looks at new ways to build shelters on the Moon or Mars using materials that are sustainable and can be made locally. Instead of bringing heavy construction materials from Earth, the project uses bio-composite panels made from natural fibers like flax or hemp and eco-friendly resins from algae or mycelium. These panels are light, strong, and biodegradable. They will be tested for strength, insulation, and resistance to space conditions. The aim is to create safe, eco-friendly, and long-lasting structures for future space missions.

Key Words: Sustainable, Bio-composites, Natural-fibers, Ecofriendly, Biodegradable.

1.INTRODUCTION

Space missions are often limited by the high costs and logistical challenges of transporting building materials from Earth, making sustainable alternatives essential for future exploration and colonization. One promising solution is the use of locally available or easily grown resources, which reduce dependency on Earth-based supplies while offering practical and eco-friendly construction options. Bio composite panels, produced using natural fibers such as hemp, are particularly attractive because they are strong, lightweight, renewable, and capable of performing well in harsh extraterrestrial environments. The incorporation of innovative binders, such as algae and mycelium-based resins, further enhances sustainability, as these materials are biodegradable and can be cultivated on-site under controlled conditions on the Moon or Mars. By enabling in-situ production, these bio composites significantly cut down the need for heavy cargo transport and help create a more self-sufficient space habitat. Moreover, these panels are not just structurally reliable; they also provide excellent thermal insulation, a critical factor for maintaining stable and safe temperatures in extraterrestrial habitats where extreme fluctuations between heat and cold can compromise crew safety. Overall, the development of biocomposite building panels demonstrates how resource-efficient, renewable, and adaptive materials can address both the scientific and environmental challenges of constructing habitats in space.

2. Literature Review

Pawlicki et al. propose the mWALLd concept—using mycelium-based biocomposites as sustainable space construction materials. The study utilized molding and 3D printing to form building blocks from mycelium grown on plant waste, sometimes reinforced with bacteria for added strength and functionality. Finite element modeling wasn't directly mentioned, but the focus on design flexibility and additive techniques is similar to modern digital fabrication approaches. The mWALLd composites are lightweight, adaptable to complex shapes, strong, and can even offer potential for self-repair and enhanced environmental performance in extraterrestrial environments

Lipińska et al. investigated the growth of mycelium in inflatable molds and mixing with local soils for in situ construction. The methodology incorporates advanced modeling of habitat architecture to optimize protective and self-healing terrestrial or space structures. The approach integrates aspects of composite theory, bioprocessing, and CAD-based shape control, allowing for habitat designs that are lightweight, customizable, and sustainable. The study highlights how rapid digital prototyping and biological "manufacturing" reduce logistical and economic costs compared to traditional construction

Shiwei et al. developed Martian biolith, a composite made from Martian regolith and chitosan, showing the advantages of combining local resources with simple, low-energy fabrication techniques (including molding and additive manufacturing). The study emphasizes the use of CAD and 3D printing for onsite construction of tools, parts, and structures, paralleling current trends in patient-specific orthotics through virtual prototyping and stress modeling. Biolith's ease of shaping and mechanical flexibility reflect the strengths of integrating composite theory with digitally driven, energy-efficient manufacturing

Lipińska et al.This work introduces an aleatory (random) construction system for Mars habitats, utilizing Martian soil, plant waste, and mycelium. The process involves robots dropping composite "blocks" that self-arrange, connected by mycelium's growth—illustrating a combination of simulation-driven design and in situ resource utilization. The approach reduces the human labor, assembly time, and hardware complexity, much like time-saving, digitally customized manufacturing seen in patient-specific orthoses. The system's flexibility allows rapid customization and adaptation to local planetary conditions

Ezeh's et al.research applies cone calorimetry, thermogravimetric, and thermal analyses to assess a fire-retardant composite of banana fiber, cow horn ash, and polyester. Variations in composite makeup were systematically tested to optimize the material's behavior under fire and mechanical stress, paralleling FE-based iteration in product design. The results underscore the importance of composite formulation and bio-inspired additive selection to enhance functionality, cost, and safety—principles also key in modern custom orthotics using 3D printing and simulation

Roy et al.This review covers bio-composite fabrication methods such as extrusion, molding, and advanced treatment techniques, highlighting the integration of natural fibers with synthetic matrices for strength, lightness, and eco-friendliness. It draws attention to how composite design optimization and digital tools can yield products tailored to application needs, advancing the field much like CAD- and simulation-driven development in orthotics and additive manufacturing

Rabbi et al. focus on injection molding of bio-composites using natural fibers (jute, hemp, flax, bamboo) with plastics. The technique involves thorough process control, surface modification, and fiber-matrix bonding, echoing best practices in digital manufacturing and simulation for optimized product strength and quality. The approach leverages versatile machines (like Battenfeld, Arburg) and addresses mass customization—key for patient-specific devices and efficient production lines

Khalid et al. extensively review natural fiber-reinforced polymer composites (NFRPCs), emphasizing their sustainable mechanical properties, widespread applications, and challenges (e.g., water uptake). Advanced chemical treatments and hybridization techniques are discussed for property enhancement, alongside the value of finite element modeling and computational simulations to predict mechanical behavior and optimize designs—mirroring the integrated digital workflow in orthotic innovation

Farhan et al.This study explores the use of flax fiber composites for aerospace, manufactured via layered treatment and compression around honeycomb structures. Panels received fire-retardant treatments and validation through rigorous fire exposure testing. The research demonstrates the potential for simulation-backed, advanced composites in critical applications, with strengths and customization similar to patient-tailored orthotic device strategies and additive manufacturing in healthcare engineering

.Fowler et al. review the development of hybrid biocomposites—materials combining natural (e.g., jute, banana, hemp) and synthetic (e.g., glass, carbon) fibers with polymers to deliver strong, lightweight alternatives for aerospace, automotive, and industrial applications. The methodology includes material selection, layering and hot pressing or hand lay-up, and a range of mechanical and thermal testing to optimize properties. The key outcomes are increased strength, reduced product weight, and reduced environmental impact, with hybridization enhancing durability and utility in demanding environments such as aircraft and spacecraft

John et al .This study by John & Thomas explains the fabrication of biocomposites using plant fibers (flax, hemp, cotton) with plastics. Classic composite processes like extrusion, molding, and fiber surface treatment are used to improve strength and compatibility. Biocomposites are promoted as alternatives for automotive and construction uses, known for their recyclability and reduced ecological footprint. Technical improvements focus on fiber length, matrix compatibility, and the shift towards bioplastics and renewable matrices, with the aim of matching or surpassing conventional composites

Ilyas et al. explore green and hybrid biocomposites reinforced with natural fibers (jute, flax, hemp) in polycaprolactone (PCL) matrices. The methodology incorporates microscopy, mechanical, and environmental durability testing, emphasizing optimized formulations for strength, flexibility, and biodegradation. Hybrid composites are tailored by varying fiber types and treatments, and these materials demonstrate low thermal and sound conductivity, fire resistance, and resistance to biological attack. The study supports the use of agricultural waste for cost-effective, sustainable product design in advanced engineering applications

Haramina et al. create epoxy resin biocomposites reinforced with flax and hemp for marine and medical uses, focusing on the impact of combining PCL with natural fibers. The process uses melting, molding, and chemical treatment to enhance fiber-matrix adhesion and property balance. The composites are validated using mechanical and thermal analysis methods, showing improved toughness, heat resistance, and biodegradability. The results confirm the effectiveness of combining PCL with plant fibers to produce safer, longer-lasting, eco-friendly engineering materials

Zwawi et al.This reviews flax and hemp biocomposites with epoxy resin, focusing on marine applications. Methodology includes layering natural fiber fabrics with partially plant-derived epoxy, curing, and performing mechanical, water absorption, and biofouling tests. Results indicate that flax performs better than hemp in most environments, especially in water resistance and retained strength after submersion. These biocomposites are lightweight, relatively strong, and with further optimization, could replace metals and glass fiber in aquatic and other demanding fields

Peças et al. analyze natural fibre composites made from materials like banana, rice husk, and jute, using blend, treatment, and molding processes (compression, extrusion, chemical/physical surface modifications). The review emphasizes progress on strength, water/fire resistance, and cost-effectiveness, discussing the improvement of interfacial bonding and the use of nanoclays or hybrid blends for better mechanical and insulation performance. The study advocates for increased adoption in automotive, construction, and packaging industries where environmental goals must be met

Palanisamy et al. address the diversity and performance of natural fiber composites (e.g., cotton, bamboo, hemp, flax), examining testing protocols for strength, durability, and processing, with focus on woven/non-woven formats. The study reviews improvements through chemical treatments and standardized testing, noting increased industry use in vehicles, furniture, and sports equipment. Challenges remain due to the variability of natural fibers, but ongoing research and industrial support drive adoption for eco-friendly, cost-effective product design

Raj et al.This article assesses the engineering of green composites from fibers like jute, flax, bamboo using several fabrication methods: hand/spray layup, filament winding, compression and injection molding. The different methods are matched to application requirements (e.g., car doors, building panels). Mechanical and durability testing show that these composites, when properly designed and processed, have properties nearing those of traditional glass-fiber composites, with advantages in cost, weight, and sustainability. The review highlights their suitability for broad commercial use across sectors

Atmakuri et al. evaluate hemp and flax fiber-reinforced eco-poxy matrix biocomposites, focusing on improved environmental performance compared to plastic. The approach uses chemical fiber treatments, molding, and 3D printing to optimize mechanical, morphological, and hydrophilic properties. Transmission electron microscopy and mechanical tests confirm that proper treatment significantly improves bonding, water resistance, and durability—making these composites attractive for replacing plastics in automotives, construction, and medical devices

Atmakuri et al.This study investigates natural fiber-reinforced composites (jute, hemp, flax in eco-poxy) for automotive, defense, and architectural uses. The methodology combines chemical treatment, hybridization, and predictive modeling (FEM, DRM) to examine water uptake, strength, and durability. The results show that hybrid fibers or chemical modifiers can achieve properties close to or exceeding those of conventional composites, supporting their use in eco-friendly, high-performance applications where customized mechanical behavior and environmental resilience are required

Alaneme et al. analyze mycelium-based composites (MBCs) in construction. The process involves selecting suitable fungi and lignocellulosic feedstocks (e.g., straw, sawdust), sterile inoculation, molding, and post-growth drying and coating. MBCs offer low density, fire safety, and good acoustics but struggle with mechanical strength and high water uptake. Best used for insulation or furniture rather than structure—future studies should enhance consistency, water resistance, and exterior durability

Camilleri et al. present a comprehensive overview of mycelium-based composites (MBCs) for sustainable manufacture. Techniques emphasize managing substrate type, temperature, humidity, and pH for optimal fungal growth, with critical post-processing (pressing, heat) to improve properties. Benefits include low embodied energy, versatile end uses, and economic feasibility. Key barriers: public acceptance, variability, and lack of standards—improving manufacturing and standardized testing is essential for widespread adoption

Roumeli et al. introduce plant cell-based composites, produced by culturing undifferentiated tobacco cells, compressing and dehydrating to form lamellar, plywood-like structures. These new materials are fully biodegradable, and their performance (e.g., conductivity, magnetism) is tunable via fillers and process changes. Mechanical properties rival PS and LDPE plastics or wood, offering a truly sustainable replacement for many standard polymers in engineering and green construction

Cuy Net et al. examine epoxy/flax composites for tensile strength using advanced digital image correlation. Flax (twill) fiber laminates (30% v.f.) are molded and tested through quasi-static experiments, with precise strain and displacement tracked by 7D image analysis. Results show consistent, repeatable tensile strength (avg. 101.5 MPa), confirming flax composites as lighter alternatives to glass fiber and validating image correlation for composite testing

Shamsuri et al. improve HDPE/agar biocomposites by adding a eutectic ionic liquid with a surfactant (HTAB), enhancing compatibility and bonding. Internal mixing (150°C), sheet molding, and mechanical testing show that HTAB boosts impact strength by 24% and tensile extension by 72%. The approach reduces filler pull-out and lowers melting points, making these bio-composites more durable, flexible, and feasible for sustainable plastic replacement

Regazzi et al. investigate bio-based flax/PLA composites (0%, 10%, 30% fiber) subjected to long-term hydro-mechanical aging (temp, water stress, mechanical creep). Tests show fibers slow crack growth and improve life under wet conditions, but high temperatures degrade elasticity and rigidity. Main drawback: water and heat sensitivity, so low-PLA composites are unsuitable near the PLA glass transition for structural use, highlighting the importance of condition-specific application

Yang et al. review mycelium bio-composites as eco-materials grown from agricultural waste under controlled humidity/temp, then dried to lightweight foams or sandwich boards. Strength depends on density, fungus type, and agricultural substrate. Properties include fire resistance and acoustic absorption. Challenges are inconsistent production, slow growth, and the need for better process control—greater research into standardization and scale-up is necessary for widespread practical use

Regazzi et al. model hydrothermal aging of short flax/PLA composites by simulating water uptake, swelling, and polymer softening at 20–50°C. Experimental and simulated data show good agreement for reversible changes (low and moderate heat), while irreversible chemical damage at higher temperatures (50°C) isn't captured. Adding more flax slows water uptake but affects swelling anisotropy, confirming the modeling approach for predicting durability under wet conditions

AL-Oqla et al. apply evolving genetic programming (GP) trees to predict green fiber (cellulose, hemicellulose, lignin, moisture, microfibrillar angle) mechanical properties—tensile strength, modulus, and elongation. GP models show microfibrillar angle and cellulose drive tensile strength, moisture and hemicellulose affect elongation, and lignin/hemicellulose influence modulus. This machine learning method enables better selection/design of biomaterials with predictable high-performance outputs

Bahrami et al. review hybrid biocomposites (mixed natural and synthetic fibers/polymers) to balance properties: strength, water resistance, flame retardancy. Preparation involves fiber/matrix selection, appropriate techniques (compression, surface treatment), and optimizing fiber-matrix bonding. Results consistently show hybrids outperform single-fiber composites in mechanics and safety—hybridization and fiber treatments are highlighted as routes to overcome the limitations of pure natural composites

Aiduang et al.This study investigates mycelium-based composites (MBCs) produced using various fungi and lignocellulosic residues like sawdust, corn husk, and rice straw. The research highlights substrate and fungal species effects on density, water absorption, shrinkage, and mechanical properties. MBCs with specific fungi show promising strength and durability, suggesting they could replace synthetic foams for packaging, furniture, and construction applications.

Yıldızhan et al. This review discusses bio-composite materials, focusing on recent trends in their mechanical and chemical properties and applications. It emphasizes the potential of bio-composites as renewable and compostable substitutes for traditional materials in manufacturing, particularly for automotive industries, while addressing challenges like moisture absorption and matrix-fiber adhesion.

Zhang et al The review covers fire-safe bio-based composites, concentrating on enhancing fire resistance while maintaining mechanical strength. It evaluates flame retardant additives and treatment methods, noting that although bio-composites are often flammable, scientific advancements have improved their safety for use in packaging, construction, and transportation industries.

Motamedi et al.This article reviews mycelium bio-composites (MBCs) as sustainable building materials, highlighting their low embodied energy and excellent thermal insulation. It addresses fabrication techniques, including molding and 3D printing, and discusses challenges related to scalability, process standardization, and durability, especially in humid conditions, while recognizing their potential for net-zero energy buildings.

Laycock et al.This paper presents biodegradable polymer biocomposites made from renewable resources, examining processing methods and degradation behavior. It points out the growing demand for bio-based composites with good mechanical properties and environmental benefits, though it also notes challenges related to fibre-matrix adhesion affecting durability and performance.

Pop et al. This study analyzes organic bio-composite mixtures made with cellulose pulp, beeswax, fir resin, and natural fillers for thermal and sound insulation. Results reveal that these composites exhibit improved thermal stability, sound absorption, and oxidation resistance, making them suitable and environmentally friendly options for sustainable building and acoustic applications.

Bojković et al.The research investigates new bio-composite materials composed of sawdust, corncobs, styrofoam granules, lime, and gypsum. It evaluates their porosity, water absorption, airflow resistance, and thermal conductivity, finding that certain mixtures, particularly those with specific proportions and thicknesses, optimize both thermal insulation and soundproofing for building uses.

Roberts et al. This study introduces extraterrestrial regolith biocomposites using human serum albumin (HSA) from blood as a binder for lunar and Martian soil simulants. The composites exhibit compressive strengths comparable or superior to concrete, with added urea enhancing strength significantly. The work showcases a sustainable local resource approach for building strong habitats in space environments.

Windra et al. This review examines fire-resistant natural fiber biocomposites, focusing on flame retardant additives and the use of lignin as a green, sustainable fire retardant. The paper discusses various techniques for improving fire resistance without compromising mechanical properties and addresses challenges such as water resistance and adhesion in these eco-friendly materials.

Ullah et al.This review covers natural fiber-based biocomposites' potential in advanced automotive applications. It discusses properties, fabrication methods, and the environmental benefits of bio-composites made from fibers like hemp, flax, and jute. The paper highlights weight and cost reductions in car parts and ongoing improvements needed for heat resistance and durability to fully replace traditional materials.

Table -1: Mechanical properties of fibers

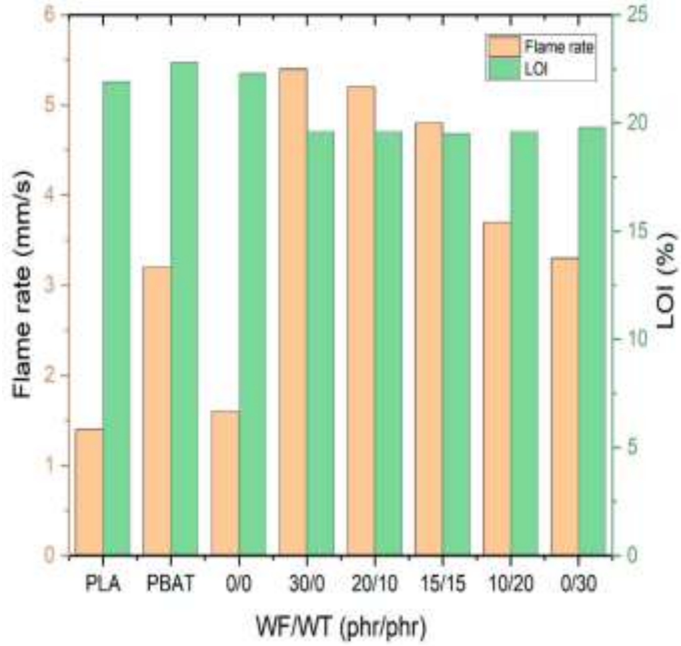
Mechanical Property		Flax–Dry	Flax–Wet	Hemp–Dry	Hemp–Wet
Tensile test	Strength (MPa)	68.6	70.4	45.7	31.3
	Standard deviation	5.4	3.3	3.7	2.0
	Modulus (MPa)	4258	1496	2648	1214
	Standard deviation	563	103	293	73
Flexural test	Strength (MPa)	73.8	39.1	81.2	60.4
	Standard deviation	6.2	10.0	14.9	11.9
	Modulus (MPa)	4302	1116	6000	3263
	Standard deviation	1184	376	1744	1300
Interlaminar	Apparent interlaminar shear strength (MPa)	10.4	20.7	9.27	6.0
	Standard deviation	0.3	3.16	1.6	0.6
Impact strength (J)		1.72	3.73	0.76	0.77

Table-2: Fibers mechanical properties

Type	Fiber	Density (g/cm³)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Elongation at Break (%)
GRASS	Bagasse	1.2-1.25	20-290	17-27.1	1.1
	Bamboo	0.6-11	140-230	11-17	-
WOOD	Hard Wood	0.3-0.88	51-210.7	5.2-15.6	-
	Soft Wood	0.3-1.5	45.5-1000	3.6-40.0	4.4
FRUIT	Coir	1.15-1.45	106-593	1.27-6.0	15.0-59.9
	Oil palm	0.7-1.55	100-400	1.0-9.0	8-25
BAST (STEM)	Jute	1.3-1.46	393-800	10-30	1.5-10.0
	Flax	1.4-1.5	345-1500	27.6-80	1.2-3.2
	Hemp	1.47-1.48	550-900	70	1.6-4.0
	Kenaf	1.2-1.45	295-930	53	1.6-6.9
	Kudzu	-	130-418	-	-
	Nettle		650	38	1.7
	Ramie	1.45-1.5	220-938	24.5-128	1.2-3.8
LEAF	Abaca	1.5	400-980	3-12	3-10
	Banana	1.35-	355-500	12-33.8	5.9-53
	Henequen	1.2-1.4	430-580	10.1-16.3	3.0-4.7
	Pineapple	0.8-1.6	170-1672	82	1.0-3.0
	Sisal	1.33-1.5	400-700	9.0-38.0	2.0-14
SEED	Cotton	1.5-1.6	287-597	5.5-12.6	3.0-10.0
	Kapok	0.38	93.3	-	-
SYNTHETIC	Carbon	1.4	4000	23-240	1.4-1.8
	E-glass	2.5	2000-3500	70.0	0.5-3.0
	S-glass	2.5	4570	86.0	2.8
	Aramide	1.4	3000-3150	63-70	2.5-3.7

Fig -1:3D Printed Fungal Composites.

Charts 1:Flamabality rate



3. CONCLUSIONS

The comprehensive analysis highlights the significant potential of bio-based and natural fiber composites as sustainable, lightweight, and eco-friendly alternatives to conventional materials. These composites combine plant-derived fibers such as hemp, flax, jute, and banana with biodegradable polymers or resins, yielding materials with favorable mechanical strength, thermal insulation, and acoustic properties. Such innovations reduce reliance on fossil-based resources, lower carbon footprints, and support circular economy principles by utilizing agricultural and industrial wastes. The scope of applications spans terrestrial industries including automotive, aerospace, construction, marine, and protective gear, as well as extraterrestrial habitat construction using local materials like Martian regolith combined with biological binders such as fungi or human-derived proteins. Despite inherent challenges like moisture sensitivity, variability in fiber quality, and flammability, advances in chemical treatments, hybridization, and innovative fabrication methods (e.g., injection molding, hot pressing, 3D printing) enhance durability and performance. Ongoing research aims to optimize production, standardize processes, improve fire resistance, and scale manufacturing to foster wider adoption. Ultimately, these materials pave the way toward greener technologies by providing versatile, high-performance solutions that align with global sustainability and environmental preservation goals..

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