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Synthetic Biology for Sustainable Material Production: Current Advances and Future Horizons

Khushi Sharma, Arun Kumar Sharma*, Yatika Dixit, Preeti Yadav, Isha Choudhary, Akshita Saxena and Khushi Agrawal[1]

Department of Bioscience and Biotechnology, Banasthali Vidyapith, Rajasthan - 304022, India; arun.k.sharma84@gmail.com

Abstract

Recent studies have demonstrated significant improvements in the efficiency of biodegradable material production, accompanied by reduced environmental impacts compared to conventional petroleum-based plastics. Microbial-derived Polyhydroxyalkanoates (PHAs) and Bacterial Cellulose (BC) represent two promising advances in this field, offering viable replacements for traditional plastics due to their biodegradability and functional versatility. In parallel, plant-derived fibres, particularly bamboo, are being increasingly explored for the development of low-impact and sustainable construction materials. Together, these innovations reflect a broader transition toward environmentally responsible material systems, integrating biological processes with material design to address current sustainability challenges. The evolution of engineered living materials enables new applications of living cells to create materials capable of self-repair and environmental responsiveness. Advanced biotechnologies such as CRISPR technology, metabolic engineering, and the implementation of cell-free platforms provide a highly tunable framework for the precise synthesis and deployment of bio-derived polymeric materials. Recent studies have reported up to a 2.5-fold increase in PHA production along with nearly a 40% reduction in CO_2emissions, highlighting their potential to mitigate environmental burdens associated with conventional plastic synthesis. Engineered biological systems are increasingly being developed as versatile platforms for applications across biomedical engineering, packaging, construction, and environmental remediation. While these advances show significant promise, challenges such as scalability, regulatory compliance, and reproducibility remain to be addressed, necessitating stronger alignment between biotechnology policy and technological development.

Major Findings: Synthetic biology facilitates up to a 2.5-fold boost in PHA bioplastic production and a 40% decline in CO_2 emissions contrasted to petroleum plastics. CRISPR and metabolic engineering allow precise modification of mechanical and environmental sensing properties in microbial, fungal, and plant material platforms. Engineered Living Materials (ELMs) successfully embed living cells into structural frameworks to achieve autonomous self-repair and responsive growth. Potential real-world applications are developing across varied sectors, comprising self-healing "living concrete," biomedical dressings, and responsive wearables. However, commercial scale-up is constrained by high production costs, biological batch variability, and an absence of standardized regulatory frameworks.

Keywords: Biodegradable Polymers, Engineered Living Materials (ELMs), Sustainable Material Production, Synthetic Biology

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1. Introduction

Modern material manufacturing is still heavily dependent on petroleum-derived plastics and high-energy production methods, which lead to increased greenhouse gas emissions, persistent plastic pollution, and loss of biodiversity[1,2]. Growing awareness of these impacts has resulted in growing interest in biofabrication, which produces materials with lower environmental costs by exploiting biological systems. Engineered living systems, which involve the systematic design and engineering of biological parts and systems, offer a rapidly expanding repertoire of methodologies for this purpose, including genetic

*Author for correspondence

circuit design, optimisation of metabolic pathways, and engineering of microbial chassis. By combining approaches from molecular biology, systems biology, computational design, and related fields, this discipline enables precise reprogramming of cells for customised functions. This comprehensive approach allows the creation of materials with customised mechanical characteristics, dynamic responses to stimuli, and reduced ecological footprints. Although progress has been rapid, many of the earlier evaluations have mostly looked at biomedical or metabolic engineering applications and haven't completely included the new advancements in making materials in a way that is good for the environment.

A more comprehensive examination is needed to bridge advances in Synthetic biological systems with material science, to highlight cross-disciplinary progress, and to identify future directions for environmentally responsible manufacturing. Cells can be treated as highly controllable micro-factories, allowing polymers, composites, and even living architectures to be engineered by researchers using genetic engineering techniques, enabling capabilities not previously achievable[3,4]. However, a unified perspective that integrates diverse biological systems and evaluates their comparative performance in sustainable material production remains lacking. The broader intersection between synthetic biology and sustainable materials is explored in this review, with particular focus on microbiome, fungal, and plant-derived systems, as well as ELMs. This review summarizes key tools and methodologies, outlines major applications and functional properties, and evaluates environmental and economic benefits.

However, much of the existing literature is examined by researchers for each material category separately, making it difficult for direct comparisons between different approaches or evaluations of their performance across entire life cycles to be made. Similarly, challenges such as genetic stability, regulatory considerations, and industrial-scale reproducibility are often marginalised in discussions. This review aims to bridge these gaps by systematically comparing microbial, fungal, and plant-based material systems. It further evaluates their functional properties, production efficiency, and potential for industrial-scale implementation. Emphasis is also placed on ELMs as an emerging paradigm that integrates biological functionality with material design.

2. Types of Sustainable Materials

2.1 Microbial Materials

Microorganisms have become one of the most promising platforms for generating sustainable biomaterials, as engineered bacteria and yeast can produce or assemble polymers with tunable mechanical and functional characteristics (Figure 1). BC, primarily produced by *Komagataeibacter* species, forms highly organised nanofibrillar structures with excellent mechanical strength, purity, and biocompatibility. Its production through simple microbial fermentation and potential for genetic modification make BC a versatile material for numerous applications. Typical BC production yields reported under optimised laboratory conditions range from (2-10g/L), although higher yields have been achieved in controlled bioreactor systems[5]. BC performance has been significantly improved by sustainable bioengineering systems, including the introduction of regulatory circuits that enhance cellulose synthase expression or the fusion of cellulose fibres with functional peptide domains. Nguyen *et al.*[6] have incorporated fluorescent proteins or metal-binding elements directly into the cellulose matrix through engineered strains, which has enabled them to create hybrid films that possess environmental sensing capabilities. In other cases, Malci *et al.*[3] and Quijano *et al.*[7] have combined biopolymers such as proteins or alginates with BC to enhance adaptability and response to environmental stimuli in areas such as wound dressings, strong textile fibres, and scaffolds made through three-dimensional printing technologies. Malci *et al.*[3] and An *et al.*[8] have discovered that these modified BC structures provide valuable applications; these studies collectively demonstrate improved functional performance rather than large-scale production readiness. Another major group of microbially produced materials includes PHAs. PHAs, as biodegradable polyesters, offer a renewable alternative to petrochemical plastics, and Vicente *et al.*[2] are increasingly being investigated for commercial applications. Advances in metabolic engineering have redirected cellular pathways to boost PHA synthesis, tune monomer composition, and improve physicochemical properties such as durability and elasticity. Garcia-Granados *et al.*[9] have expanded the structural diversity and performance of PHAs through the application of genome editing platforms such as CRISPR-Cas and TALENs, which they combine with high-throughput design tools[2]. Industrial PHA production systems have

reported yields typically in the range of (20-80g/L) depending on the organism and process configuration, highlighting progress toward scalability[10].

However, despite promising laboratory results, full-scale commercialisation continues to be limited by issues such as high production costs and variable mechanical strength[2]. While bacterial cellulose and curli-based materials remain largely at laboratory or pilot scale, PHA production has reached partial commercialisation in specific industrial settings. Another important microbial route is provided by curli-based materials derived from *E. coli* biofilms. Amyloid nanofibers (CsgA) are naturally inherent by the curli system, to which functional peptides have been engineered by Nguyen *et al.*[6] to display on the fibre surface. Such modified fibres can bind heavy metals and organic contaminants, thereby facilitating their accumulation and potential transport in the environment. Nevertheless, the challenge of scaling biofilm-based materials from laboratory to industrial production remains substantial[4,6]. Parallel initiatives to produce artificial spider silk made in microbes are also developing. The exceptional elastic properties of spider silk proteins, which are called spidroins, arise from their remarkably large and repeating structures[11].

Various bioengineering strategies, including computational protein design, directed evolution, and optimisation of microbial hosts, are now being actively investigated to enable reliable and expandable production, although current yields are often limited (commonly <1-5g/L in microbial systems), restricting industrial translation[11]. These advancements demonstrate that microorganisms can be rationally engineered to produce a wide range of polymers and protein-based materials with tunable properties.

Microbial systems, as mentioned before, have a variety of great traits, including being easily adaptable, using renewable or waste-based feedstock, and producing biodegradable and bioabsorbable materials. Despite these advantages, industrial implementation remains uneven: many processes are still confined to pilot-scale operations, with only a limited number achieving consistent commercial-scale operations, with only a limited number achieving consistent commercial-scale production. Several companies stand out due to, for example, Mango Materials, which produces PHA using methane-derived feedstocks at pilot-to-early commercial scale, and Genomatica, which operates at commercial scale for certain bio-based chemical production processes using engineered microorganisms. In recent years, both researchers and industry practitioners have increasingly turned their attention to artificial microbial consortia, deliberately designed communities of microorganisms that work together to perform specific metabolic functions. These engineered systems enable more efficient production processes while helping sustain higher and more stable yields. To successfully bridge the gap from laboratory discovery to actual manufacturing, it is vital that researchers, industry executives, and other specialists identify the need to encompass ecological principles, construct scalable bioprocesses, and test these processes in real-world contexts. The effectiveness of these genomic interventions is evidenced by research yielding a 2.5x increase in PHA production compared to wild-type strains, demonstrating the power of pathway optimisation in microbial chassis[2].

2.2 Materials Derived from Fungi

Comprehensive mycelial networks are made by filamentous fungi, including molds and mushrooms, which are gradually recognised by researchers as valuable building blocks for new classes of biomaterials (Figure 1). When mycelium is encouraged by farmers on agricultural remnants, it can be grown into buoyant froth-like composites, which offer a supportable and ecologically accountable alternative to petroleum-based plastics and conventional animal leather[12]. In natural habitats, fungi break down organic substrates using effective enzymatic systems; in engineered settings, Vandelook *et al.*[13] exploit this same ability to bind herbaceous biomass into bind herbaceous biomass into adhesive material structures. By inoculating lignocellulosic waste such as husks or wood chips with selected fungal species, structured composites are

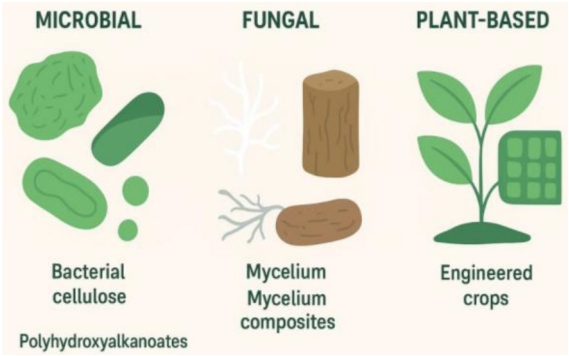


Figure 1. Types of sustainable materials derived from microbial, fungal, and plant sources.

formed through hyphal growth and interweaving. The mechanical properties of these composites, ranging from flexible to highly rigid - can be tuned by particular fungal strains being selected, growth parameters being modified, or post-processing treatments being applied[13]. Strong, lightweight foams suitable for uses such as isolation and wrapping are known to be made by species such as *Ganoderma* and *Pleurotus*, which produce white-rot mycelium. Leather-like or sponge-like materials can also be made from mycelium when it is processed without additional substrates, emphasising the potential of mycelium to substitute both petrochemical polymers and animal-derived products[12].

Even though the progress in biodesign has traditionally been condensed on bacteria by researchers, thought is immediately being given to fungal systems by them. Filamentous fungi possess prominent metabolic diversity, secrete large amounts of functional molecules, and naturally form fibre-based structures, which gives them great potential for biological engineering. The advancement of fungal synthetic biology frameworks has been hindered by technical challenges, including low transformation efficiency, slow growth rates, and limited availability of genetic tools. Approaches, including mutagenesis, directed evolution, and computational modelling, have been outlined in recent reviews to help overcome these Barriers for improving the performance[14]. Faster-growing strains are targeted to be designed by current research, the secretion of pigments or mycolic chemicals for colourful materials is aimed to be augmented, and hyphal growth patterns are aimed to be transformed to influence the mechanical strength of mycelium composites[15] - an area that is still in its early stages[14,15]. Despite early progress, it is acknowledged by both major reviews that fungal biofabrication remains in a formative stage: Niche commercial markets have been reached by mycelium materials, but achieving industrial-scale reproducibility is noted to remain difficult due to limited understanding of fungal biology[12].

Nonetheless, circular-economy principles are well aligned with fungal materials, with waste streams being utilised as substrates and being biodegraded naturally at end-of-life[12,13]. Encouraging discoveries are starting to appear. For example, the expression of chitin synthase genes has been increased through CRISPR-Cas9 editing of *Aspergillus nidulans*, resulting in an enhanced mycelial matrix, while structural protein secretion has been improved by metabolic reconnection in *Trichoderma reesei*, which has led to improved composite intensity and Coherence. Such advances exhibit how the gap between genotype and material performance in filamentous fungi is being closed by engineering biology, with pathways being arranged toward more expected and extensible bio-composites. Even so, the literature highlights that researchers still face significant research disputes. Many studies continue to present descriptive findings rather than mechanistic insights, and researchers often find that direct links between genomic modifications and the resulting material traits are lacking. Addressing this gap will require scientists to develop improved fungal engineering toolkits, including optimised promoters, more efficient CRISPR platforms, and reliable transformation systems, to enable a rational and predictable design of fungal materials[12,15]. The transition from these micro-scale laboratory successes to macro-scale utility requires a shift in how we perceive biological outputs. While individual polymers like PHA and BC demonstrate the functional feasibility of synthetic biology, their true potential for the built environment lies in their integration into bulk building materials and structural composites.

2.3 Plant-based Materials

Plants have evolved as efficient natural producers of structural biopolymers such as cellulose, lignin, and natural rubber (Figure 1). The capabilities of these native traits are now either expanded or replicated within microbial hosts by Yang *et al.*[16] through biodesign. One major direction is direct plant genetic modification, which enables the environmentally sustainable production of fuels, chemicals, and materials to be supported by decreasing resource consumption and associated emissions[16]. Recent progress in the botanical engineering discipline showcases advancements such as CRISPR-based editing, synthetic promoter libraries, and single-cell omics tools that enable researchers to achieve highly targeted, tissue-specific or cell-type-specific trait expression[16]. For example, Garcia-Granados *et al.*[17] have engineered tobacco (*Nicotiana tabacum*) to accumulate polyhydroxy alkanoates (PHAs) within chloroplasts, effectively converting the plant into a capable biological production platform for biodegradable plastics. Likewise, natural rubber biosynthesis has been enhanced through modifications made to Russian dandelion *(Taraxacumkok-saghyz),* leading to a more sustainable alternative being provided to the traditional rubber tree (*Hevea brasiliensis*) while cultivation in cooler climates is being supported[18].

As a precedent, alterations to lignin biosynthesis have lowered resistance to processing in popular resulting in efficiency being improved for industries such as pulp, paper, and biofuels[19].

A complementary approach is to have plant polymer synthesis replicated outside of the plant itself using microbial or cell-free platforms. For instance, plant-like cellulose or lignin precursors may be produced through *in vitro* fermentation with tunable properties. Although still comparatively underexplored, such strategies could eventually allow engineered microbial consortia to manufacture composite materials that mimic plant-derived structures. Reviews on bioplastics highlight the necessity to contemplate all such materials, whether from plants, algae or microbes, within a circular framework. This approach causes renewable biomass as a feedstock and designs products for recycling or safe degradation at end-of-life. Though agricultural trade-offs are also carried by the Extensive cultivation of engineered crops. Competition with food production and land-use constraints must be carefully managed during large-scale cultivation of engineered crops. Therefore, viability is not biotechnological developments but also on land availability, Economical efficiency, scalability, and environmental concerns. If these challenges can be discussed, significant potential is held by sustainable materials to become both eco-friendly and economically viable, particularly at industrial scales. Still, several technical barriers are being faced. Transformation rate is often regarded as low, Biochemical pathways are known to be highly regulated and complex, and innovation can be slowed by regulatory overload, although the field of plant-based biological construction is still rising and somewhat visionary, particular advantages are provided by it, such as biological carbon fixation through photosynthesis, direct production of complex polymers in plant tissues, and the possibility of localised or distributed manufacturing systems. Yet, the translation of laboratory proof-of-concept works to real-world production remains slow due to long crop growth cycles and yield limitations[16]. Model species like *Arabidopsis thaliana* and tobacco *(Nicotiana tabacum)* are also heavily concentrated on by current research, resulting in a gap in tools and platforms that are optimised for high-yield, field-relevant crops. Bridging this divide will require linking advanced biomolecular engineering approaches, such as plastid engineering and synthetic chromosomes, with agricultural species that can perform at a commercial scale. Only then will the full promise of plants as sustainable material factories be realised. However, the evolution of sustainable manufacturing extends beyond simply replacing fossil-based feedstocks with plant or microbial derivatives; it seeks to retain the inherent 'vitality' of the biological system. This conceptual shift leads to the emergence of ELMs, where the focus moves from inert bio-composites toward integrated frameworks that remain alive and responsive to their surroundings. While these biological systems provide the structural basis for sustainable materials, their functional optimisation relies on advanced synthetic biology tools.

3. Tools of Synthetic Biology for Materials

To enable the precise design and fabrication of biological materials, synthetic biology relies on a diverse set of molecular and computational tools. Recent progress in biofabrication results from rapid advancements in this discipline, which researchers support with a sophisticated collection of genetic engineering tools. Central to this toolkit, scientists utilise modern DNA assembly methods such as Gibson and Golden Gate assembly, along with extensive libraries of standardised biological components, including biobricks and synthetic promoters, as well as increasingly precise genome editing systems. Techniques like Gibson assembly and CRISPR-Cas9 now make it possible for multi-gene pathways to be reconstructed or modified in a seamless manner, enabling efficient rewiring of metabolic routes for polymer production[16,10]. Additionally, fine control over gene expression in a wide range of engineered hosts is allowed to be exerted by Yang *et al.*[16] and Garcia-Granados *et al.* [10] using synthetic promoters, riboswitches, and other regulatory elements. Metabolic engineering frameworks are further integrating multi-omics datasets and computer-driven modelling to enhance metabolic flux toward desired bioproducts, with rational pathway optimisation being directed by quantitative models[10]. Even in filamentous fungi, which have long been viewed as formidable for genetic modification, adapted CRISPR-based systems and recombineering techniques are now helping to subdue longstanding obstacles[15].

Beyond DNA-level interventions, the physical construction of materials is being shaped by biodesign through emerging fields such as synthetic morphology, bioprinting, and controlled bioassembly. Spatial patterning

of living materials with predefined architectures is enabled by bioprinting using cell-laden hydrogel inks, including those containing bacterial or fungal cells. Bacterial cellulose-based ELMs have already been structured into complex forms through this approach in 3D printing[3]. Genetically modified organisms can also be organised into patterned structures through programmed chemotaxis or differential adhesion. A fundamental role is played by computational design in this ecosystem: new silk-like proteins, adhesive motifs, and other functional domains are being generated through artificial intelligence-driven protein engineering. A strong example of this workflow is offered by the development of microbial spider silk-repetitive protein sequences, which are informed in their design by computational modelling, while expression and production yields are helped to boost by directed evolution and microbial host engineering[11].

A bridge between genetic design and the resulting material properties is ultimately provided by computational modelling. Increasingly, these models serve as tools for:

- *Molecular modelling*: molecular modelling to predict the effects of changes in selected (genetic) elements on protein/biopolymer folding, assembly and subsequently, on the resulting key physical properties (*e.g.*, tensile strength, elasticity, and biodegradability) of the engineered/ fabricated material[20].
- *Hierarchical modelling for systems-level understanding*: Multiscale models are able to integrate various biological and physical dimensions of information related to gene regulation, protein interaction, as well as their collective mechanical performance, and therefore represent a complete system-level view of the overall performance of a bio-fabricated material[20].

3.1 Advances and Challenges in Iterative Biofabrication Workflows

These workflows use computational predictions that feed directly into the next iteration of the Design-Build-Test (DBT) workflow, enabling faster optimisation and reducing the reliance on slow, trial-and-error experimentation (Figure 2). Another emerging direction involves cell-free and minimal biological systems. Although researchers' use of these systems in constructing large-scale bulk materials is still limited, several studies have shown that cell-free protein synthesis can serve as a rapid platform for prototyping material-related proteins and pathways[21]. Mixed microbial consortia are also being engineered by synthetic biologists, functioning as distributed "fabrication factories," in which specific roles are each carried out by different species, such as a polymer being synthesised by one microorganism while a corresponding cross-linking enzyme is produced by another[14,22]. Taken together, these advances span multiple layers and are spanned by the available toolbox, from fundamental molecular genetics to computational and bio-design software. Biofabrication is described by most authors as following a modular, iterative Design-Build-Test methodology[9,22]. However, in the field, a persistent barrier faces: the difficulty of transferring genetic tools across various biological systems. Researchers often find that genetic circuits optimised in the model organism *E. coli* require extensive revalidation when they are used in non-model hosts such as fungi, algae, or emerging bacterial chassis. Engineers face a major challenge in developing reliable, transferable parts that function predictably across diverse organisms. Additionally, while researchers have rapidly advanced DNA construction

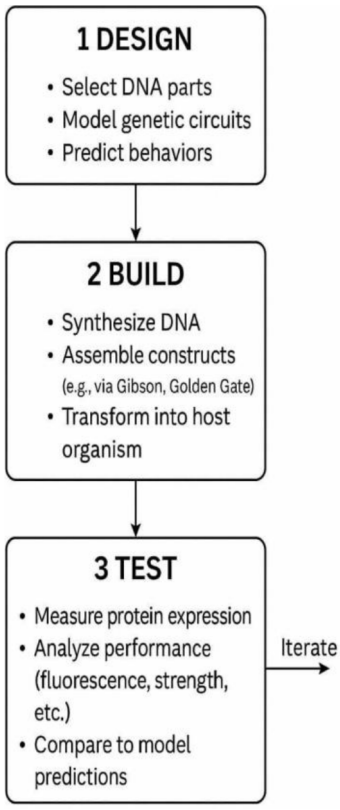


Figure 2. The DBT Loop: An iterative approach for constructing and evaluating engineered biological systems.

technologies, the corresponding tools for characterising final material performance lag behind; in particular, they still encounter a scarcity of predictive frameworks that directly link genetic circuits to large-scale mechanical behaviour.

4. ELMs

The sophisticated "smart" behaviors that characterize ELMs—such as autonomous self-healing, environmental sensing, and adaptive growth—are not inherently natural traits but instead emerge through precise genomic engineering and reprogramming. To achieve this level of architectural and functional control, researchers rely on a highly specialised molecular toolkit, with CRISPR- based systems and metabolic engineering serving as the primary drivers for rewiring cellular logic. A new class of materials is represented by ELMs, where living cells are integrated directly into the Structural fabric, and thereby imparting dynamic and responsive properties to the material (Figure 3). Unlike Traditional compositions that remain compliant after invention, ELMs enable active growth, damage repair, and interaction with their environment in a versatile approach. Recent work by An *et al.*[8] positions ELMs as the junction of constructive biology and modern materials technology[4]. With their main characteristics such as independent growth, adaptive behaviour, and the performance of scheduled functions in reaction

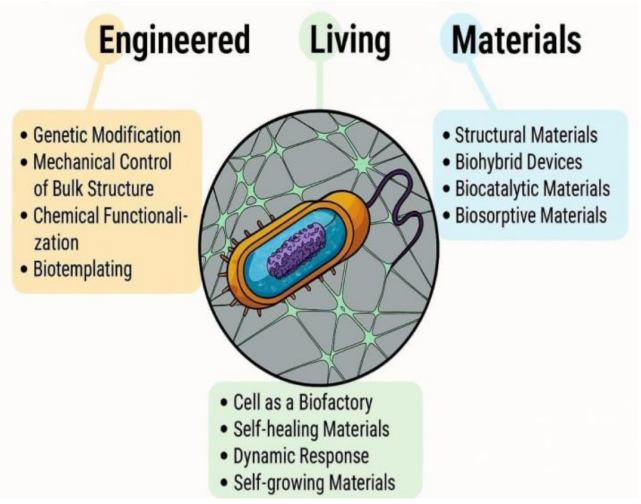


Figure 3. Engineered Living Materials (ELMs) are hybrid systems embedding living cells within material frameworks, enabling self-repair, environmental responsiveness, and on-demand biosynthesis through genetic engineering, surface modification, and biotemplating.

to environmental prompts[8,22], Roldan *et al.*[23] present practical examples such as "living concrete" where a mineral matrix immobilises engineered microbes and promotes crack repair, and vesture biosensing platforms integrate engineered cells rooted in polymer networks that change colour when vulnerable to specific toxins[8]. Despite these advancements, ELMs continue to face significant limitations before broad adoption can occur. Key challenges include secure long-term operative stability, maintaining expected behaviour in exterior laboratory environments, increased manufacturing, and integrating these biological systems into current industrial materials. Biocontainment is of particular concern, referring to the need to stop engineered organisms from living or disseminating beyond the implied context. Strategies to achieve this are included, such as synthetic auxotrophy, where engineered cells are made to depend on non-natural nutrients for survival; and genetic kill-switch systems that are designed to trigger cell death under certain conditions; and programmed lifespan mechanisms that have defined genetic "timers" introduced to control how long cells remain active in the material.

Engineered Living Materials (ELMs) are represented as a new class of advanced systems in which designed material frameworks are combined with living cells to produce structures that are capable of growth, self-repair, and environmental adaptation. By the programming of cellular behaviour through molecular and genetic engineering, dynamic responses to external cues can be elicited by these materials. A variety of prototype ELMs are presented in the literature through demonstrations, such as the work of An *et al.*[8] examples are provided that include the embedding of spores or microbial cells within silica gels or polymer matrices to create functional biohybrids Self-reporting wall components have produced as a result of recent advances, in which Changes in humidity are indicated by bacteria Integrated into brick-like materials, and wearable textiles that include engineered yeast capable of producing silk on demand have created, along with interfaces such as biofilm-coated electrodes designed for localised energy capture[8,22]. A central conceptual insight is that the bottom-up self-assembly principles of biological systems are merged with the top-down control typical of materials engineering by ELMs. Nguyen *et al.*[4] illustrate this relationship in comparative models that show how a biological system, such as a tree developing from a seed, parallels an engineered system that engineers build from modified cells[4] Experts widely regard ELMs as promising

contributors to sustainability. Numerous articles describe various applications in renewable energy, such as living photovoltaic devices, environmental remediation through pollutant-sequestering materials, and next-generation medical devices[8]. Comprehensive assessments also have the potential of ELMs in eco-architectural design and sustainable building highlighted, where waste is vigorously reduced, and biodegradability is endorsed by biotic factors, representation on the minimal ecological footprint associated with biological fabrication[1,22]. However, it is found by most researchers that most ELM systems remain at laboratory or proof-of-concept scale and converting them into practical products upholds important open questions.

These questions include how to maintain biological function over long deployment periods, how to manage unintended genetic variations, and how to support cellular viability in environments well beyond controlled laboratory settings. Although the promise of ELMs presents significant potential, their increased use raises serious concerns regarding biosafety, genetic reliability, and the risk of unintentional biological activity. One important concern that arises is genetic drift or spontaneous mutation, which may progressively erode engineered traits or create unpredictable phenotypes[4,23]. Further divergence from the original design may be caused by environmental pressures, evolutionary selection, or horizontal gene transfer, with the possibility for system failure or ecosystem imbalance to follow[24]. Furthermore, activity could be resumed by dormant or cell encapsulation under Ecological triggers, leading to uncontrolled growth or persistence in locations outside the intended staging area[25]. To control these risks, current research[26] brings to the force on robust isolation systems such as synthetic auxotrophy (forcing dependence on unnatural nutrients), genetic kill-switch mechanisms that are activated by external stimuli, and automated life spans that restrict how long engineered cells are allowed to remain active. It is therefore needed that regulatory guidelines extend beyond basic laboratory containment to include guidelines for environmental release, long-term monitoring, post-deployment oversight, and deactivation procedures[27]. The need for strong collaboration among synthetic biologists, materials scientists, policymakers, and bioethicists is underscored by these considerations to ensure that ELMs progress from promising concepts to safe and responsible real-world technologies.

5. Applications

5.1 Construction and Packaging Applications

Biologically produced materials are increasingly being evaluated for their potential use in the building and packaging industries. Mycelium-based composites are already commercially available in the form of foam-like bricks and insulation panels, demonstrating their potential to serve as direct replacements for petroleum-derived materials such as polystyrene[12,13]. Several emerging companies are genetically modifying fungal strains to improve characteristics like pigmentation or hydrophobicity, although peer-reviewed validation of many of these claims remains limited. Attention for applications in sustainable textiles and filtration systems has similarly been gained by bacterial cellulose due to its high mechanical strength and breathability[2,4]. Meanwhile, compostable packaging is being explored with PHAs, and production processes that use industrial and food waste streams to improve economic feasibility[2] are being investigated in current research.

5.2 Biomedicine and Advanced Textiles

Within biomedical applications, wound dressings are especially valued for their use of bacterial cellulose because of its purity, biocompatibility, and ability to retain moisture at the injury site[3]. Scaffolds for tissue repair are also being developed using synthetic versions of structural proteins such as collagen and silk. Medical uses such as sutures and bandages have been tested with engineered spider silk produced in yeast[11]. While bacterial systems have been used to produce mussel-inspired adhesives for surgical sealants and wearable electronic contacts. These examples illustrate how molecular engineering can be combined with polymer science to create hybrid biomaterials with finely tuned performance traits.

5.3 Living Wearables

Living wearable technologies bridge the realms of fashion, biotechnology, sensing, and responsive design. For example, engineers create fabrics embedded with engineered bacteria that can undergo visible colour changes when they are exposed to UV radiation, airborne pollutants, or other environmental factors. This integration of biological sensing with textile engineering actively introduces the exciting possibility of clothing that can provide real-time environmental feedback to the wearer.

5.4 Environmental Remediation

Environmental remediation is another developing field of application. Wang *et al.*[22] developed materials embedded with engineered microorganisms to capture pollutants, including heavy metals and organic contaminants derived directly from water sources[4,22]. These systems can also support continuous pollutant breakdown through engineered biofilms that act as living filters. While these examples demonstrate significant promise, the majority of such applications still remain at experimental or small-scale demonstrations. Much of the research in environmental ELM deployment is still in the early stages, and researchers will need to conduct larger pilot studies in real operational environments to evaluate long-term feasibility and performance[22]. Utilising these bio-based alternatives offers significant ecological advantages, with current studies indicating up to Co_2 emissions during the material synthesis phase, effectively mitigating the carbon footprint associated with traditional plastic production.

5.4.1 Smart Environmental Sensors

Chen *et al.*[28] designed living biosensors developed as ELMs to change fluorescence output or mechanical characteristics when exposed to environmental contaminants. These materials may exhibit altered structural or functional properties. Van Duijkeren *et al.*[29] merge microbial genetic engineering with materials design and low-power sensor technologies in these systems, making them particularly attractive for remote or low-maintenance applications in environmental monitoring[30].

5.4.2 Sensors and Smart Responsive Materials

A distinctive strength of living materials is that built-in sensing elements can be acted upon by biological components[31]. Therefore, "smart" materials, such as ELMs, have been proposed as capable of having their properties altered in response to external stimuli[32]. For example, fluorescent signals can be produced, or stiffness can be modified by engineered bacteria when toxic compounds are detected. As Koller *et al.*[33] describe, environmental signals can be sensed by cellulosic or protein-based ELMs, and programmed responses can be initiated by them. Such applications can be supported by these systems, ranging from the monitoring of structural integrity in built environments to personalised wearable diagnostics. However, it is noted that most demonstrations remain at the proof-of-concept stage, which is performed under controlled laboratory conditions, and the ability to function consistently in real-world environments has yet to be demonstrated.

5.4.3 Opportunities and Limitations

Taken together, these technologies emphasise several common themes: they exploit the biodegradability, biocompatibility, and self-generating nature of living systems[3,8]. It is widely acknowledged that capabilities-such as adaptation, self-repair, and dynamic sensing-are possessed by materials engineered through biomolecular engineering, which are not possible in traditional inert materials[8,22]. However, it is also cautioned by the literature that many of these breakthroughs remain in the category of scientific promise rather than routine practice. In many cases, it is only limited experimental studies that support specific claims, making conclusions provisional. For example, while encouraging performance has been shown by bacterial cellulose wound dressings[3], ongoing is the large-scale clinical adoption. Likewise, proposals for "living architecture," such as training trees or ELMs to serve as structural elements, remain largely visionary rather than commercially realised technologies.

5.5 Self-Growing Furniture

Recent experimental work in bio-architecture has been demonstrated by Jones *et al.*[30] to show that fungal mycelium or plant root systems can be guided to grow within designed molds, leading to the formation of load-bearing furniture and structures without the need for conventional manufacturing methods. This blending of biological growth, sustainable design, and architectural practice is introduced as a new paradigm for environmentally centred material innovation.

Table 1 provides an outline of how biodesign is being applied across Broad sectors, including construction, healthcare, Environmental reconstruction, and receptive "smart" materials. This overview outlines significant material platforms, such as bacterial cellulose, mycelium-based composites, and engineered biofilms and determines their functional roles, ranging from segregation and Wound healing to emission control and the growth of programmable Biological systems[4,8,23,31].

5.6 Ecological Continuity Ideas

In synthetic biology, Vicente *et al.*[32] focus on diminishing sustainability challenges by decreasing dependence on

Table 1. A wide range of application areas is being explored for ELMs. The accompanying table is provided to summarise the different material platforms or technological strategies that are used, along with their corresponding practical applications, and the key sources in literature that support these developments.

Application	Material/Technology	Key use	References
Common themes	Biocompatibility	Found across multiple application domains, but remain largely experimental	[8]
Construction and packaging	Mycelium composites PHAs, BC	Insulation panels, foam-like bricks, and sustainable packaging	[8]
Biomedicine and textiles	BC synthetic analogues of collagen and silk, Engineered adhesives (mussel foot protein)	Wound dressings, tissue scaffolds, surgical glues, and wearable electrodes	[23]
Environmental remediation	ELMs with bacteria-engineered biofilms	Sequestering toxins (*e.g.*, heavy metals), pollutant breakdown	[4]
Sensors and Smart Materials	Fluorescent/programmable	Found across multiple application domains, but remain largely experimental	[31]

fossil fuels through the strategic advantage of renewable feedstocks[1], enhancing the biodegradability of products at end-of-life to reduce persistent waste[33], and actively adjusting with the principles of recycling management by employing agriculture and food waste as precious feedstock[34]. Examples of bio-based sustainable materials are recognised, including PHAs (polyhydroxyalkanoates), which are fully biodegradable and derived from renewable carbon sources, and are shown to alleviate plastic pollution under both aerobic and anaerobic conditions[33,35]; BC, which can be produced from agro-industrial waste such as molasses or fruit peels[36] and is deemed suitable for low-energy, high-purity bio manufacturing; and the bio-upcycling of plastics is achieved using engineered *Pseudomonas* and *Cupriavidusnecator* strains that convert PET-derived monomers into PHA, thereby enabling a "plastic-to-bioplastic" transformation[37,38].

Positive findings are revealed by Life Cycle Assessment (LCA) insights: The assessments are further corroborated by findings showing that metabolic optimisation in microbial systems can yield a 40% decrease in CO_2 emissions. This metric is particularly significant when evaluating the shift toward a circular bioeconomy, as it demonstrates a measurable reduction in the environmental burden compared to traditional polymer synthesis[39]. It is noted that PHAs from waste feedstocks emit 40-80% less greenhouse gases than polyethylene in comparative LCAs[39], and it is indicated that bio-based BC uses 30-60% less water and energy compared to fossil-based films[36]. However, trade-offs and cautionary considerations exist. It is suggested that bio-based systems may displace food crops and use more water than petrochemical processes[1]. It is often stated that compositing and biodegradation rates at end-of-life are overestimated in real-world scenarios[40]. Moreover, it is noted that PHA production remains economically challenging, being 5-10 times costlier than polyethylene without subsidies[41].

Emerging concepts include eco-design of biosystems, where systems are engineered for function, circularity, low energy use, and modular repair[1], with tools like metabolic modelling and biosafety switches[42] being utilised; and bio-upcycling, where plastic waste such as PET and PS is enzymatically depolymerised and re-synthesised into biopolymers like PHA or PLA by using engineered microbial consortia[34,37]. Regulatory and risk assessment considerations are included in evolving regulatory frameworks such as REACH (EU) or TSCA (US) to evaluate biosynthetic materials[43]. Aspects like engineered organism release, and persistence and gene transfer risks in soil/marine environments are now incorporated by Environmental Risk Assessments (ERA)[44]. A unified biosafety and sustainability framework is recommended for ELMs and synthetic biopolymers[45].

6. Challenges and Research Gaps

Despite major scientific progress, scaling biological production systems remains a tenacious challenge. Most demonstrations are still carried out in laboratory-scale bioreactors ranging from a few millilitres to a few litres. When these systems are run at industrial volumes, new complications frequently emerge, including

contamination, reduced culture stability, and variability in product performance. For ELMs, additional issues are introduced by increasing fabrication scale, such as the need to manufacture large, uniform material blocks without compromising biological activity[4]. Similarly, consistent growth across sizable molds is required for the large-scale production of mycelium-based composites, yet only a limited number of studies are provided with empirical data on maintaining such uniformity.

A second major gap concerns achieving predictable control over emergent material properties. Biological systems inherently show batch-to-batch variability, and although many traits can be tuned, they may drift over time or shift in response to minor environmental fluctuations. This problem is particularly acute in living materials, where system performance can be changed by mutation, evolution, or genetic rearrangement. While genetic stability is acknowledged as a critical obstacle by several reviews[46,47], scarce remain the experimental datasets that explore long-term performance under realistic environmental conditions. Indeed, instability arising from metabolic burden in synthetic circuits has been documented by some studies[48], and it is emphasised by others that engineered traits can degrade over evolutionary time. The importance of robust biocontainment systems and genetic safety mechanisms for real-world deployment is reinforced by these issues[49]. A further limitation is the narrow range of biological chassis available for engineering. The optimisation of most molecular toolkits is done for a small number of well-characterised organisms such as *Escherichia coli* and *Saccharomyces cerevisiae*, along with a few model plant systems. The extension of these capabilities to non-model hosts- including filamentous fungi, cyanobacteria, and complex microbial consortia- requires the development of new regulatory elements, vector systems, and transformation strategies[14,9]. Unresolved barriers are also presented by regulatory and societal considerations. Biosafety and governance questions are raised by the introduction of ELMs into buildings, consumer products, infrastructure, or natural environments. For instance, the release of a genetically modified organism is effectively constituted by deploying a self-healing architectural material- but how such cases should be evaluated is rarely addressed by the literature. Guidelines or regulatory frameworks are called for by only a few forward-looking publications, while scientific methods are focused on exclusively by most technical papers. An important gap for future policy development is highlighted by this lack of discussion. Finally, pace has not been kept by functional validation with conceptual innovation. Many proposed applications-such as living insulation boards or self-repairing road surfaces-remain largely theoretical, and substantial experimental backing is lacking. In several cases, reviews describe a planned usage without citing definite empirical displays, which suggests that experts nowadays think of these ideas as conjectural. For this reason, authors often use careful words like "potential," "may," or "suggests" when talking about these developing technologies.

Economic feasibility remains a critical limitation for large-scale adoption. Techno-economic analyses indicate that bio-based polymers such as PHAs remain significantly more expensive than conventional plastics without subsidies or process optimisation. Additionally, the lack of standardised production protocols and performance benchmarking limits cross-study comparisons and industrial reproducibility. Variability in biological systems further complicates manufacturing consistency, particularly in large-scale bioreactor systems.

7. Overcoming Future Challenges

Researchers are working rapidly to bring biodesign to commercial use, but many barriers still separate research from successful commercial and environmental applications. between researchers and the successful use of biodesign in commercial and environmental applications. A critical gap persists between laboratory-scale innovation and its reliable translation into industrial and real-world deployment. One example is the movement of ELMs from a small experimental level to large-scale industrialisation. ELMs grown from microorganisms or as biofilms have successfully developed as prototypes under controlled laboratory conditions[50]. However, in order for these types of products to be used in large-scale production, ELMs must demonstrate appropriate biocontainment and exhibit stable engineered behaviour in a variety of conditions throughout the production process[4]. In particular, ensuring long-term genetic stability and preventing unintended ecological interactions remain key unresolved challenges. Variation in mechanical properties from cycle to cycle must also be addressed, as this remains a challenge for industry (Figure 4). The connection between advanced materials engineering and such methodologies needs to be enhanced as the production

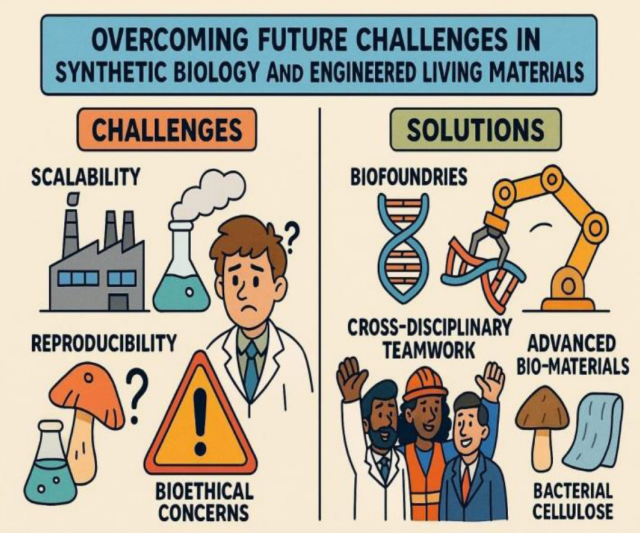


Figure 4. Key challenges and future directions in biodesign and ELMs.

of engineered cells needs to consistently yield stable and predictable results under a wide range of batch sizes, manufacturing locations, and changes in environmental conditions[14]. The commercial use of these technologies will be limited until reproducibility can be established. Besides the challenges in technology, significant changes in government policies and ethical rules surrounding synthetically produced biological products are required to shape living systems engineering and the use of synthetic products as they grow increasingly essential for sustainable manufacturing and the future development of sustainable materials and sustainable products. Existing regulatory frameworks often lack clarity on long-term environmental risk assessment, standardised biosafety protocols, and mechanisms for public accountability. Regulations that are in place need to remain relevant and up-to-date. Current government regulatory frameworks for biosafety and Intellectual Property are inadequate and missing long-term ecological impacts and public transparency. Building Public Confidence in using synthetic biological products may require promotion of good engineering practice and an open, collaborative approach to engineering. Transparent reporting systems and standardised validation procedures could further strengthen trust among stakeholders and regulatory bodies. Infrastructure and expertise must also be improved and increased to allow the field of ELMs to mature. ELM progress will require both advances in biology as well as the conjunction of computational modelling, materials science and regulatory policy[3]. A commitment made to invest in Cross-Disciplinary Education, Research, and Modular Biofoundries will support the design, testing and development of new sustainable materials platforms, by utilising the expertise and capabilities of these individuals, institutions and equipment[8]. Such integrated platforms can accelerate design-build-test cycles and reduce the time required for process optimisation. To address limitations associated with microbiological systems, it will be necessary for researchers and developers to use new design tools that support the development of multiple types of microbial chassis. In addition, using more advanced tools for working with genetic circuits will reduce the uncertainty of biological behaviour caused by the molecular environment within the macromolecular chassis. Currently, the first generation of custom Cell-Free Chassis (CFC) provides a stable platform to test new genetic circuits outside of live cells, thereby reducing variation and instability during the initial testing and evaluation of those circuits[51]. These systems enable rapid prototyping and facilitate more controlled characterisation of genetic components prior to *in vivo* implementation in parallel, Interchangeable design Libraries-such as SynBioHub, SBOL (Synthetic Biology Open Language), and ICE (Inventory of Composable Elements), actively support the sharing and reuse of genetic modules, which in turn promotes plug-and-play engineering across different organisms[51]. However, inconsistencies in data standardisation and annotation still limit their full interoperability across platforms. Although the calibration processes across the various organisms are progressing rapidly, the reality is that many researchers are confronted with challenges when trying to implement genetic tools that work well in commonly used laboratory species; these tools sometimes behave differently with less-studied microbes, plants and fungi[52]. Many researchers also cite the limitations of context-dependent responses, which restrict the ability to transfer genetic designs efficiently between species. To combat these limitations, scientists are attempting to create orthogonal genetic parts and, for example, using insulated promoters or CRISPRi-based logic gates to create more robust engineering methods. Despite these advances, achieving predictable cross-species function remains an ongoing challenge due to complex intracellular interactions. Nonetheless, even with these efforts and significant gains in many instances, scientists across disparate biological groups experience varying degrees of accomplishment. The absence of universal standards

will impede the ongoing global progress on the scalability and overall efficiency of engineering workflows, slowing down the overall expansion of the field and limiting future growth[53]. Establishing widely accepted design standards, performance metrics, and validation frameworks will be essential to enable consistent scalability and industrial adoption.

8. Future Directions

Looking ahead, it is anticipated that research in Biodesign and ELM will become increasingly interrelated with rising computational and mechanical platforms. A key future direction lies in integrating predictive computational modelling with experimental workflows to enable cost-effective and scalable material design. A significant shift will likely involve wider adoption of robotics and high-throughput automation to guide the rational design of genetic circuits able to improve the material support, performance, and long-term functional reliability[54,55]. Automated biofoundries are imagined as facilities that can quickly build and evaluate extensive libraries of engineered variants, thereby enabling large-scale investigation of structure-function relationships. However, the lack of standardised data formats and reproducible experimental pipelines currently limits the full potential of such platforms. Technologies such as modern multilocus assembly methods, CRISPR-based epigenetic regulation, and minimal artificial cells functioning as highly optimised production systems will also be enabled from future biodesign[56,57].

Broad convergence across disciplines will continue to be considered essential. Interconnected input from molecular biologists, Crystallographers, and environmental scientists will be required to design living materials whose behaviour is governed from the genetic to the architectural level. For example, the possibility of emerging for the manufacture of complex hybrid systems, such as printed frameworks incorporating bacterial, fungal, and even plant cells-through advances in 3D bioprinting, which are making emergent behaviours attainable that are not possible in single-species systems. Pathways toward new applications ranging from adaptive clothing to structural elements capable of renewal may be opened by such mixed-kingdom ELMs. Additionally, an evolutionary model for resource-limited or isolated environments is offered by the concept of "*in situ* biomanufacturing," where materials are produced directly at the site of use, such as in Underground construction supported by soil microbial activity. However, technological developments alone will not create sufficient impact. Economic feasibility and process scalability remain underexplored, particularly in terms of techno-economic modelling, cost-benefit analysis, and supply chain integration for large-scale deployment. The broader literature identifies a persistent lack of regulatory framework, public engagement, and established frameworks for academic property management encompassing ELMs. In parallel, the absence of universally accepted standards for characterisation, performance benchmarking, and lifecycle assessment continues to hinder cross-study comparisons and industrial translation. The questions of classification of self-regenerative biological structures, along with long-term assurance of ecological safety, remain largely unresolved. Open access to resources and transparent development processes, as well as meaningful public engagement during the design and implementation of these systems, will play an important role in addressing these issues. There is great potential for aligning Biodesign with a circular economy, but this must include both life cycle assessment and carbon accounting in any designs to ensure long-term sustainability. For example, Tiso *et al.*[36] are exploring the potential of using autotrophic microbes for the fixation of CO_2 from the atmosphere into bioplastics, and also developing engineered enzymes to degrade persistent petroleum-based plastics, such as PET, so that the by-products can be used to generate more feedstocks. Despite these advances, inconsistencies in data reproducibility across laboratories and variability in biological performance under industrial conditions remain major barriers to validation and scale-up. Pilot studies will be required to confirm the feasibility and scalability of such methods within actual industrial and environmental contexts. There are still many questions to be answered regarding the above-mentioned topics of this discipline; however, one promising area has been the creation of gene circuits capable of directing the sequential assembly of materials. Another area is the development of interchangeable "material modules", or genetic parts with well-defined properties, which can be assembled within plug-and-play workflows. Standardisation of such modules, along with improved documentation and database integration, will be essential to ensure their widespread usability. Another area researchers must improve is developing strategies to increase durability and stability (i.e. finding new ways to

keep freeze-dried biological materials alive over time). Scientists are looking for ways to fill in the gaps of the developing field that links genotype and phenotype quantitatively. While ELMs are generating a lot of excitement, the greatest challenge to overcome is how to get from laboratory demonstration to real industrial and social use. Key manufacturing bottlenecks- including batch-to-batch variability, scale-dependent performance shifts, and limitations in bioreactor design- must be systematically addressed to enable reliable production. Collaboration among experts will be required to achieve technical progress, solve manufacturing problems, and address the impact on society and the environment of using living systems in the built environment. Successfully transitioning ELM technologies into practice requires a systems-level approach with the support of pilot-scale testing, collaborative action with many different stakeholders, and transparent governance. For Synthetic Biology and ELMs to reach their potential, coordinated involvement from researchers, policymakers, industry, and communities will be necessary to build a sustainable, globally scalable biofabrication system. Through collaboration, the experimental systems we now have access to will evolve into adaptive, regenerative, and environmentally restorative materials.

9. Conclusion

Biodesign is expanding rapidly as it challenges conventional assumptions about how materials are developed, manufactured, and applied. It demonstrates how researchers are creating materials with useful functional capabilities. These materials are often produced through environmentally sustainable methods and are designed to be biodegradable. Some can even self-repair through the reprogramming of living organisms such as bacteria, fungi, and plants. This field integrates biomolecular engineering, computational design and materials science. Together, these approaches enable the development of polymers, composites, and living materials. The resulting materials possess properties that are not achievable through conventional chemical manufacturing processes. Through collectively combining various biological platforms (bacterial cellulose, polyhydroxy alkanoates, fungal mycelial composites and other bio-based polymers), material production is gradually being redirected toward circular and sustainable production models. Nevertheless, significant obstacles still exist to enable widespread use of Biopolymers. These include the hardships of large-scale production, the ability to preserve genetic stability, and the lack of a clearly defined regulatory framework, which must be addressed to maximise the potential benefits that Biopolymers can provide. In order to be successful moving forward, more collaboration between scientists, business, and government is required. Future biodegradable products will come combining biodesign with automation, AI, and lifecycle assessments to produce consistently performing product lines that are safe and economical to produce. It is believed that as this area continues to grow and develop, biodesign will also affect how companies connect with their surrounding environment. The advancements in technology will provide a new way to build renewable, sustainable products for future generations. By incorporating biologic principles into the design of biodegradable materials, we can build innovative products with additional benefits beyond just being environmentally friendly; our products will improve efficiency, utilise less energy, and take up less physical space than traditional products.

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Authors Contributions

KS took the initiative to design and write the manuscript. AKS undertook the responsibility of supervising the work. YD played a key role in assisting with the review and editing of the manuscript. PY, IC, AS, and KA collaborated to review the manuscript thoroughly. All authors carefully read and subsequently approved the final version of the manuscript.

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