



BIOMANUFACTURING FOR SUSTAINABLE GROWTH AND DEVELOPMENT IN VARIOUS SECTORS- A REVIEW

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Biomanufacturing, a green production process that turns waste into services, is critical for long-term development and the expansion of the bioeconomy. It uses little chemicals and ingredients, making it eco-friendly. The high rate of climate change needs the substitution of environmentally harmful activity. Biomanufacturing advances have boosted bioprocess sustainability, scalability, and competency, preparing them for industrial usage. However, problems such as numerous ministries monitoring India's biomanufacturing industry, a weak private biotech financing climate, and a change in focus from basic to applied research can all result in lower-quality research. The BioE3 (Biotechnology for Economy, Environment and Employment) policy intends to promote high-efficiency biomanufacturing in India, with the goal of creating an independent, affluent, clean, and sustainable country. The policy promotes innovation, scale-up, and biomanufacturing of speciality chemicals, enzymes, biopolymers, smart proteins, veterinary products, precision biotherapeutics, and services. Modern technology has significant implications for industrial applications, particularly large-scale bioproduct manufacturing. For successful bioproduct manufacturing, bioprocesses must be upgraded from the laboratory to the industrial scale. This chapter discusses the BIOE3 policy and provides an overview of sustainable biomanufacturing, which includes a variety of sectors where biomanufacturing is being used for long-term growth, such as high-value bio-based chemicals, biopolymers, enzymes, small protein and functional foods, prevention bio-thermotherapy, climate resilient agriculture, carbon capture and utilisation, marine and space research.

Keywords: Biomanufacturing, BIOE3, Environment, Research, Sustainability.

Introduction

Advanced biomanufacturing, or biomanufacturing 4.0, is anticipated to play a significant role in the sustainability revolution of the twenty-first century¹. This technique produces biomolecules for the food, energy, pharmaceutical, and agricultural sectors using biological systems. Biomanufacturing encompasses bio specific design constraints, bio design, bio mechatronics, bio fabrication, and assembly. It also fosters interdisciplinary cooperation and provides information for

entrance into the business. Specific design criteria, including as dependability, resistance to corrosion, biocompatibility, customisation, and controllability, are needed for biomedical goods. The 'Biomanufacturing' collaborative workgroup was formed by the International Academy for Production Engineering with the aim of designing new techniques and integrating existing technology to meet the issues associated with biomedical manufacturing. In order to lower healthcare expenses and improve quality of life, medical systems and

gadgets are crucial. Industry 4.0, a digital revolution, will put artificial intelligence, software, and advanced technologies like three-dimensional printing at the forefront of industrial customisation. Because 3D printing can create living models of tissues and organs that traditional engineering techniques cannot, it has completely changed the scientific community. This is especially helpful for those waiting on organ transplant waiting lists since 3D printed organs have lower engraftment rejection

rates because they don't remember their host. Regenerative medicine is another field where 3D printing is increasingly essential since it expedites labour and lowers treatment costs. Usually, technological innovations are little steps that enhance current technology to satisfy consumer demands. Disruptive biomanufacturing technologies prioritise cost reduction, adaptability, and process efficiency to provide businesses a competitive advantage².

Table 1. Summary of Biomanufacturing Timeline.

HISTORY OF BIOMANUFACTURING						
	Pre-Modern Biomanufacturing	Biomanufacturing 1.0	Biomanufacturing 2.0	Biomanufacturing 3.0	Biomanufacturing 4.0	Biomanufacturing 4.0 Today
Needs and Products	Fermented Products	Primary Metabolites	Secondary Metabolites	Proteins and Enzymes	Bioenergy, New food, Translational Research	Sustainable Society
Methods	Mixed cultures + solid state ferments	Monoculture + anaerobic Liquid Ferment	Monoculture + anaerobic Liquid Ferment	Recombinant DNA Techniques + cell cultures	IPS+ME & SB+PE+ivSB	Cloud Technology, Chassis engineering, Biological Design Automation
Timeline	1860s	1910s	1940s	1980s	2000s	Nowadays
Key persons	Louis Pasteur	Chaim Weizmann	Alexander Fleming	Paul Berg		

History of Biomanufacturing

Over the years, biomanufacturing has undergone many revolutions, with each one concentrating on production systems, distinct product categories, and research technologies. Despite not comprehending fermentation, pre-modern biomanufacturing changed food supplies through spontaneous mixed-culture microbial activity. Biomanufacturing 2.0 concentrated on specialised mutant and aerobic submerged liquid fermentation for

secondary metabolites, while Biomanufacturing 3.0 concentrated on advanced cell culture for large-size biomolecules and recombinant DNA technology. Biomanufacturing 1.0 was centred on mono-culture fermentation for primary metabolites. Novel products such as human tissues or cells, synthetic biology-driven microorganisms, isobutanol fermented by metabolic engineering and artificial starch might be the focus of biomanufacturing 4.0. Biomanufacturing

4.0 seeks to solve important challenges such the water crisis, energy and sustainability, health concerns, climate change, and conflicts related to the energy, food, food security and water nexus by concentrating on these breakthroughs³. Timeline depicting the developmental history of biomanufacturing has been illustrated in Table 1.

Biomanufacturing Sectors for Sustainable Development and Growth

The relevance of producing bioproducts in everyday life has led to a notable boom in the bioprocessing industry during the past

ten years. This expansion has been fuelled by improvements in biological processes and technological breakthroughs. Biomanufacturing, employs biotechnology to generate green goods and services, contributes considerably to sustainable development by transforming waste into services, stimulating innovation, and establishing a knowledge bioeconomy. The acceleration of climate change makes it imperative to substitute environmentally harmful activities⁴. Utilising waste and byproducts as microbial fermentation feedstock is one sustainable technique that helps to promote a circular economy and

Table 2. Compilation of Bio-manufactured naturally derived plant Protein based biopolymers.

Plants Proteins			
S. No.	Biopolymers	Sources	Remarks
1.	Soy Proteins	Soyabean seeds	Used in food packaging, medical applications, adhesives
2.	Pumpkin Proteins	Pumpkin seeds	Used in medicine, food, bioactive chemicals, health
3.	Wheat gluten	Wheat plant and its variety	Used in coating and films, bioplastics, thickening agents, adhesives
4.	Zein	Maize seeds or corn	Used in pharmaceuticals, plastics, paper coating, gene delivery, edible films

Table 3. Compilation of Bio-manufactured naturally derived animal Protein based biopolymers.

Animal Proteins			
S. No.	Biopolymers	Sources	Remarks
1.	Casein	Cow milk	Used in food, medicine and dietary supplements, textiles, leather, soapmaking, paints
2.	Collagen	Bovine skin and tendons; rat tail; porcine skin, intestine, or bladder mucosa	Used in wound healing, tissue engineering, corneal implants, dermal fillers
3.	Gelatin	Fish wastes, pork skins pork and cattle bones and ligaments	Used in cosmetics, biomedical, photography, paper, textiles, food

lessen reliance on fossil fuels. Bioprocess innovations have improved the sustainability, scalability, and competency of bioprocesses, making them more appropriate for industrial usage. Modern bioprocessing prioritizes

sustainability by minimizing environmental impact and enhancing economic viability⁵. Illustration of different sectors where biomanufacturing supports sustainable growth has been shown in Fig 1.

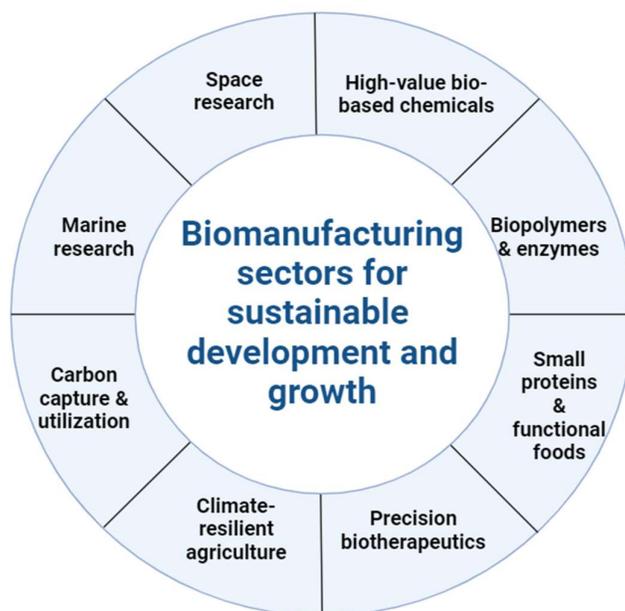


Fig.1. The illustration of various sectors where biomanufacturing is being used for sustainable growth.

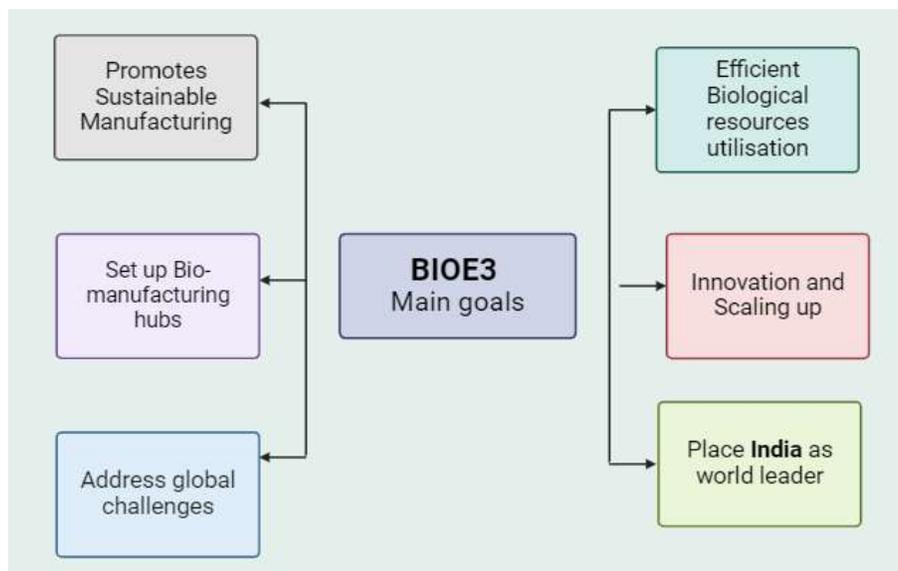


Fig 2. BIOE3 (Biotechnology for Economy, Environment, and Employment) Objectives, as per launched by Government of India

Important sectors that contribute to sustainable growth:

- **High-Value Bio-Based Chemicals**

Bio-based chemicals are essential for a low-carbon, circular economy since they are high-value resources made from low-value goods or waste. Non-food starch, fatty acids, tall oils, cellulose fibres and fermentation products like citric acid and ethanol are a few examples. Agricultural residues, or yellow biomass, are utilised to make biogas and biofuels. Sustainable products are the goal of biorefineries, which generate bio-based chemicals and polymers from renewable resources⁶.

- **Biopolymers and Enzymes**

Biopolymers are naturally occurring polymers obtained from non-food crops that are compostable, renewable and biodegradable. Because of their biocompatibility, adaptability, and bio absorbability, they are non-toxic, biodegradable, and often utilised in medical science. Biopolymers comprise cellulose,

protein, chitin, starch, DNA and RNA, to name a few. In addition, they find use in food additives, packaging, cosmetics, and medicinal products⁷. The pharmaceutical, food and cosmetic sectors frequently utilise biopolymer materials derived from natural collagen because of its exceptional mechanical and technical qualities, low toxicity, and excellent biocompatibility. Because of the growing market need and difficulty of extraction, green biomanufacturing is attracting attention. Developments in synthetic biology enable heterologous protein expression in a variety of settings, optimising the bioactivities and synthesis of collagen⁸. In Table 2, 3, 4 & 5 naturally derived biopolymer examples has been compiled. Table 6 contains the compiled information regarding synthetic biopolymers. Table 7 is the compilation of microorganism’s biopolymers in biomanufacturing. Table 8 and 9 are compilation of various bio-manufactured enzymes.

Table 4. Compilation of Bio-manufactured Naturally derived polysaccharide-based Biopolymers.

Polysaccharides			
S.No.	Biopolymers	Sources	Remarks
1.	Starch, Starch derivatives	Potatoes, maize, cassava, rice, sorghum, wheat	Used in food packing material, paper and textile, adhesives, antimicrobial activity
2.	Cellulose, Cellulose derivates	Wood pulp, bamboo, sugar beet, potato tubers, cotton, jute	Used in biobased materials, water treatment, cosmetics, plywood glues, bioactive compounds
3.	Gums	Seed epidermis and plant source	Used in tissue engineering, soil stabilization, heavy metal removal, pharmaceuticals
4.	Pectins	Citrus fruits and apples	Used in supercapacitors, edible films, food
5.	Alginates	Seawood	Used in microencapsulation, heavy metal adsorbent, food and beverage, Regenerative medicine
6.	Chitin	Corals, lamp shells, sponges, squid, cuttlefish, and clams	Used in drug delivery, pharmaceuticals, ophthalmology, food packing, wound healing, wastewater treatment
7.	Chitosan	Fungi, molluscs, algae, crustaceans, and insects	Used in bone and cartilage tissue engineering, dental disease management, toxic metal removal

- **Small Protein and Functional Foods**

The need for protein and the world's expanding population are putting strain on the food supply. There is an increasing need for high-quality dietary protein as the world's population grows. One potential substitute for traditional animal protein manufacturing techniques is cultured meat. By growing muscle cells in bioreactors with the right cell culture media, this meat is produced without utilising animals and may be more efficient and sustainable than traditional meat⁹.

Natural or industrially processed foods that, when consumed on a regular basis as part of a varied diet, may provide health benefits beyond basic nourishment, such as

promoting optimal health and reducing the risk of one or more noncommunicable diseases, such as cancer, stroke, type-2 diabetes, and cardiovascular disease (CVD). These foods are known as functional foods. The most widely available functional food products include yoghurt, cereals, butter and margarine, and protein and energy bars and drinks. Many food-processing technologies have emerged during the past 20 years, including microwaves, high hydrostatic pressure, pulsed electric fields, and ultrasounds. These ecologically friendly, sustainable methods stop microbiological growth, maintain natural nutrients in fruits and vegetables, consume less energy, and allow for the utilisation of by-products.

Table 5. Compilation of Bio-manufactured Naturally derived lipid-based biopolymers.

Lipids			
S.No.	Biopolymers	Sources	Remarks
1.	Bee wax	Glands of honeybees	Used in coating, cosmetics, candles, leather goods, wood treatment
2.	Carnauba wax	Leaves of carnauba palm	Used in biodegradable packaging, molds for semiconductor devices, dental floss, solvents and oils, printing inks, food
3.	Oils	Vegetable oils	Used in oil recovery and bioremediation

Table 6. Compilation of Bio-manufactured Synthetically derived Biopolymers.

Synthetic Biopolymers			
S.No.	Biopolymers	Sources	Remarks
1.	Polylactic Acid	Fermented sugar like sugarcane or sugar beet pulp and starch from corn, tapioca, maize that produces lactic acid	Used in injection molding, roto molding, bottles, textiles, packaging, films
2.	Polycaprolactone	Lignocelluloses polysaccharides, mucopolysaccharide biopolymer that comes from chitin	Used in 3D bioprinting, implants, dental applications, tissue engineering, drug delivery
3.	Polyvinyl Alcohol	Commercially by hydrolyzing polyvinyl alcohol with methanol in the presence of sodium methylate or sodium hydroxide	Used in Film materials, Hydrogels, Medical applications

Table 7. Compilation of Bio-manufactured Microorganisms Biopolymers.

Microorganism Biopolymers			
S.No.	Biopolymers	Sources	Remarks
1.	Polyhydroxy alkanooates	Microalgae and marine habitats	Used in agriculture, bone cement, tissue engineering, therapeutic agents, packaging
2.	Polyhydroxy butyrate	Lactobacillus acidophilus, Methylobacterium rhodesianum, Ralstonia eutropha,	Used in disposable items, energy storage, packaging materials, medical applications

• **Precision Biotherapeutics**

Sustainable development is the goal of precision biotherapeutics production through biomanufacturing, which combines cutting-edge technology with eco-friendly practices. By emphasising cleaner production and a regenerative economy, this strategy increases the sustainability of the biopharmaceutical industry. However, the transition between durable manufacturing cycles and disposable technology raises questions about sustainability. Novel medications and therapies are made possible by methods such as microbial fermentation, cell culture, biocatalysis, and recombinant DNA. Microfluidics, in vitro transcription and translation, and automated laboratory-scale batch processes provide more flexible manufacturing that also results in higher-quality products, smaller facilities, more productivity, and lower prices. Innovative industrial enzymes and renewable biomass are being studied and developed for green biomanufacturing, especially for biopharmaceuticals and other bioproducts. Biotechnology offers a promising alternative to traditional methods, enabling efficient, sustainable, and precise synthesis of complex molecules¹⁰.

• **Climate Resilient Agriculture**

Using methods that support farmers in adapting to climate change and ensuring food security is known as climate resilient agriculture. These methods include resilient infrastructure, sustainable farming practices, efficient use of water resources, resilient nutrient management, and animal

management. Forty percent of the world is affected by water shortage; effective irrigation, infrastructure for collecting water, and farm design may all contribute to water conservation. Crop nitrogen absorption is maximised and greenhouse gas emissions are decreased by nutrient management¹¹. Designing a farm with climate resilience involves building weather-resistant structures, irrigation systems, and storage facilities. Sustainable cropping methods guarantee that crop yields will be resilient enough to handle the hazards associated with future climate change. The management of livestock is essential to food security. Using weather forecast products, planting strategies that adjust to extreme weather, long-term creation and dissemination of microclimatic database repositories, and sustainable fisheries and livestock are further objectives of climate resilience farming. Maintaining farmers' economic viability while maximising national, regional, and local effectiveness is critical to meeting the nutritional needs of the world's expanding population. It is necessary to put into practice the processes that optimise production while minimising adverse environmental consequences. All disciplines, including agrotechnology, robotics and automation, and chemical-pharmaceutical process technology, require high-quality, easily-accessible infrastructure. While collaboration is encouraged, project financing is required for wide distribution.

• **Carbon Capture and Utilization**

The research explores the use of woody biomass for carbon capture and the circular bioeconomy, with a focus on the 3R (i.e. Remove, Reuse and Recycle) principles of carbon capture, utilisation, and storage and their potential to lead to a net-zero carbon

bioeconomy. Although microbial cell factories provide ecologically friendly alternatives to conventional industrial processes, it may be challenging to reconcile the allocation of carbon. The utilisation of CO₂ from the environment,

Table 8. Compilation of Bio-manufactured Enzymes like Protease, Amylases, Lipases, Cellulases and Pectinases.

Enzymes			
S.No.	Enzymes	Sources	Application
1.	Proteases	Latex of papaya plant (Papain), microbes and calf stomach	Food processing, meat tenderization, stain removal, silk degumming, leather processing, wastewater treatment
2.	Amylase	Raw fruits and vegetables and microorganisms	Fuel production, distilling, food, textile, detergents, brewing, paper
3.	Lipases	Epiglottis of sheep, goat, human milk, plants and vegetables, Rhizopus, etc.	Biodiesel, biodegradation, biosensors, medicine, food, cosmetics, wastewater treatment
4.	Cellulases	Streptomyces, Clostridium	Pulp and paper, food processing, animal feed, biofuel, textiles
5.	Pectinase	Bacteria, fungi, yeast, plants	Coffee and tea fermentation, fruit juice and wine clarification, oil extraction, poultry feed and bioenergy production, textile

Table 9. Compilation of Bio-manufactured Enzymes like Catalases, Phytases, Hydrolases, Invertases and Lactases.

Enzymes			
S.No.	Enzymes	Sources	Application
1.	Catalases	Bovine liver, sweet potatoes, bananas, Aspergillus Niger	Bioremediation, cellular processes, textile and food industry, antioxidant, protection from hydrogen peroxide
2.	Phytases	Plants, microorganisms, and blood of vertebrates	Reduces phosphorus excretion and pollution, improving nutrient utilization and mineral absorption, bakery and brewery
3.	Invertases	Yeast, fungi, plants, bees, humans	Food and pharmaceutical industry, cosmetic, drug and paper industry, functional foods
4.	Lactases	Bacteria, fungi, yeast and small intestine of humans	On commercial scale develop products free from lactose for lactose intolerant people, frozen yogurt production
5.	Hydrolases	Animal, bacteria, fungi	Bioremediation, cell culture, cell wall protein extraction

industrial wastes, or microbial fermentation as a feedstock for biomanufacturing should be researched in order to achieve carbon-neutral or -negative goals and address potential issues. Microalgae is a renewable energy source that can solve the energy crisis and reduce CO₂ emissions while producing high-value chemicals, biofuels, and nutrients. On the other hand, low productivity sometimes precludes industrial applicability. Green industrial production might be facilitated by improvements in gene editing techniques and optimisation¹².

- **Marine Research**

Marine habitats have historically yielded rich pharmaceutical resources; nevertheless, the ocean is now being discovered as an undiscovered supply of naturally occurring molecules with therapeutic potential through bioprospecting and screening for bioactive metabolites. These substances may be used to treat cancer, autoimmune illnesses, and chronic inflammatory conditions due to their anti-inflammatory and immunomodulatory qualities. Utilising biotechnology to sustainably use marine resources is essential¹³. Research uses response surface methods to optimise the preparation conditions for β -chitosan generated from diatom biomanufacturing, producing β -type that is very homogeneous and has a low molecular weight. For large-scale uniformity, the alkalisation freeze-thaw process offers a workable option. For biomanufacturing oligonucleotides, *Rhodovulum sulfidophilum* high-density perfusion cultures are used, yielding titres two orders of magnitude greater than those reported in literature. Exploration of marine microbial hosts and the potential of microalgal marine proteins for biofuel production is crucial.

- **Space Research**

Deep-space missions, such as the manned landing on Mars and the Moon, are investigating the possibility of creating homes in space for bioengineering and surgical repair. Advanced physical skills and

specialised equipment are needed in these environments for the creation, upkeep, and surgical implantation of tissue substitutes. Since pharmaceuticals usually run out after two years of being manufactured, crewed missions lasting longer are improbable. Astro pharmacy is a platform for the on-demand synthesis of peptide drugs through the use of genetically modified bacterial spores or cell-free systems. Because of their exceptional capacity to generate complex secondary metabolites and resistant endospores, marine *Bacillus subtilis* isolates have the potential to be used in the development of novel biotechnologies and space exploration goods¹⁴.

BIOE3 (Biotechnology for Economy, Environment, and Employment)

The objective of the BioE3 (Biotechnology for Economy, Environment, and Employment) as shown in Fig. 2. is to foster high-efficiency biomanufacturing in India with the goal of building an independent, wealthy, clean, and sustainable country. In the areas of speciality chemicals, enzymes, smart proteins, scaling up, veterinary goods, precision bio-therapeutics, and services, the policy encourages innovation, bio-polymers and biomanufacturing. In addition to improving domestic biomanufacturing capacity and addressing climate change, it fosters the integration of digitalisation and artificial intelligence with advances in "omics" and upstream biotechnology¹⁵. The program also creates pre-commercial and scale-up biomanufacturing facilities that are co-located with infrastructure and resources, and it develops a group of highly qualified individuals. This will support fair and sustainable resource management for Bharat as well as bioeconomic growth. Biotech hubs aim to bridge knowledge gap between manufacturing and research, fostering job growth in Tier 2 and 3 cities. BIRAC (Biotechnology Industry Research Assistance Council) and DBT (Department of Biotechnology) promote industry cooperation, innovation, and research¹⁶.

Challenges

The freezing-thaw processes, facility design, contamination, real-time control systems, product loss, ethical issues, protein engineering and technological accessibility are only a few of the difficulties that biomanufacturing must overcome. Several ministries supervising the biomanufacturing sector in India, a weak private biotech funding environment, and a shift in emphasis from fundamental to applied research are some of the challenges facing the business. The shift in focus might result in lower-quality research, because infrastructure availability is essential for biotech research. Cloning, altering organisms, and using human embryos all raise social and ethical questions. As a result of urgent human concerns about clean water, climate change, food security, sustainable development and new biomaterials, unique biomanufacturing platforms have developed quickly¹⁷.

Conclusion And Future Prospects

An essential, environmentally benign, and sustainable production mode for the expansion of the bioeconomy is biomanufacturing. It doesn't require many chemicals or materials that pollute the environment when they break down. Metabolites and microbial cells are used in the classic bioprocess to recover commercially viable compounds with improved stability and recyclability. Although smart biomanufacturing has the potential to boost productivity, there are still technological challenges, especially when collecting large amounts of data. Biomanufacturing has several benefits, such as increased sustainability, reduced energy use and innovation stimulation. It may also be used to space travel, enhancing its usefulness and versatility for solitary space exploration missions. The process of chemical biomanufacturing may help cut down on greenhouse gas emissions. Using microbes, biomanufacturing may produce bulk chemicals, food goods and enzymes. Finally, bioprinting technology is needed to

generate human tissues and organs of clinical quality¹⁸.

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