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PERSPECTIVE

A framework for the sustainability implications of 3D bioprinting through nature-inspired materials and structures

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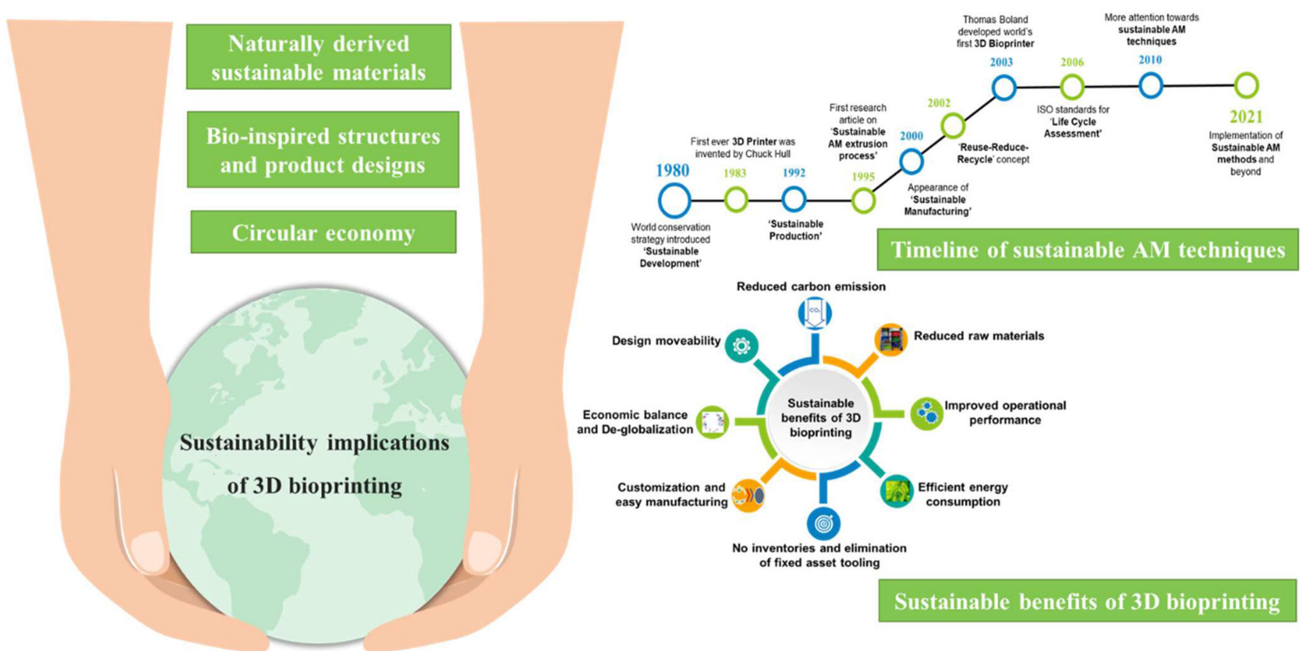
Graphic abstract



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Introduction

The climax of the industrial revolution was marked by the rapid growth of industry, and advancement in technologies have further fueled this industrial expansion, leading to a surge in economic growth. However, these technologies have also increased the degree of destructive human interference with the biosphere, as key contributors to two urgent environmental problems: deterioration of natural resources and global climate change. It is thus the need of the hour to promote cleaner, sustainable production practices using renewable energy sources [1] to better utilize resources in ways that minimize effects on the environment. Among the destructive effects of current industrial practice, automotive, aerospace, and power generation industries are prime contributors of carbon emissions. Between 1950 and 2010, total worldwide energy consumption increased 5.8 times, and CO_2 emissions increased sharply from 310 to 390 ppm during the same time period [2]. This sharp increase in carbon footprint is a central cause for sudden temperature fluctuations and global climate change.

In addition to these direct environmental effects of current industrial practice, the excessive utilization of non-recyclable materials and conventional manufacturing methods pose risks to energy security. Various manufacturing techniques were compared in this view; additive manufacturing (AM) techniques have proven to be a promising approach for designing sustainable manufacturing practices [3]. The global advent of AM technologies has revolutionized the manufacturing sectors by creating complex physical structures with excellent mechanical characteristics that can improve operational performance [4, 5]. AM has helped to eliminate the shortcomings of subtractive manufacturing techniques with minimal usage of raw materials and effective energy utilization [6]. In particular, lightweight components with improved mechanical strength can be constructed using AM techniques for aerospace and automotive applications. This approach has led to environmental and sustainable benefits like reduced carbon footprint and better resource utilization [7, 8].

One example of AM manufacturing is the use of three-dimensional (3D) digital models, which can be converted into physical models with defined materials and controlled process parameters. 3D bioprinting is a subset of AM technique, a layer-by-layer additive approach used for making artificial 3D tissue constructs from biomaterials either without living cells (functional constructs) or incorporated with living cells (cell-laden construct). Over millennia, nature has evolved to produce high-performance materials and structures; the techniques of bioprinting aim to take advantage of natural design to improve the sustainability and effectiveness of industrial design. Sustainable biomaterials should be non-toxic, recyclable, and extracted from the environment in an ecologically responsible manner. Natural products such as keratin extracted from chicken feathers, hydroxyapatite from eggshells, and pectin extracted from fruit pulp are innovative examples of sustainable biomaterials. These sustainable biomaterials are gaining profound attention than synthetic biomaterials [9, 10]. The use of 3D bioprinting in tissue engineering has generated promising results in the field of medical science, including applications in tissue and organ regeneration, prosthetics, and implants. These medical applications, along with dental materials, biological inks, biosensors, and food and animal products (cultured meat), comprise the prominent share of the current global 3D bioprinting market [11].

The distinctive physicochemical properties of biological nature, including integrated structure–function relationships, provide enormous inspiration for the design of next-generation industrial materials. Bioinspired structures promote the design of physical characteristics that save material and energy by benefitting the environment through the reduction of carbon footprint [12]. Bioinspired structures processed by 3D printing currently include applications such as sustainable vascularized microtissues, honeycomb branched biomimetic microstructures for study of cancer cell migration, lotus-root like biomimetic materials for cell delivery and tissue regeneration, and other uses [13–15]. The timeline of development of sustainable AM techniques is shown in Fig. 1.

Integration of sustainability with 3D bioprinting also facilitates realization of the concept of co-existence of human beings with nature in productive harmony. By considering environmental and socio-economic factors in product design, bioprinting sustains the needs of present and future generations. A survey of the literature indicates that sustainable manufacturing is a key tool for protecting the environment; in particular, 3D bioprinting enhances the feasibility of sustainable manufacturing [3]. This perspective aims to evaluate the sustainable solutions created through 3D bioprinting technology by incorporating nature-derived materials and structures into industrial design. It elucidates the increased demand for 3D bioprinting in the health care, food and agriculture industries, and considers how factors such as energy conservation rate, the optimal recycling rate of surplus raw materials, production time, carbon management strategies, and other factors can affect human society and the global environment. In this study, we aim to familiarize readers with the sustainable materials and bioinspired structures used in 3D bioprinting technology. We focus on 3D bioprinting as a manufacturing resource for cleaner production and offer predictions of future directions for creating sustainable industrial value.

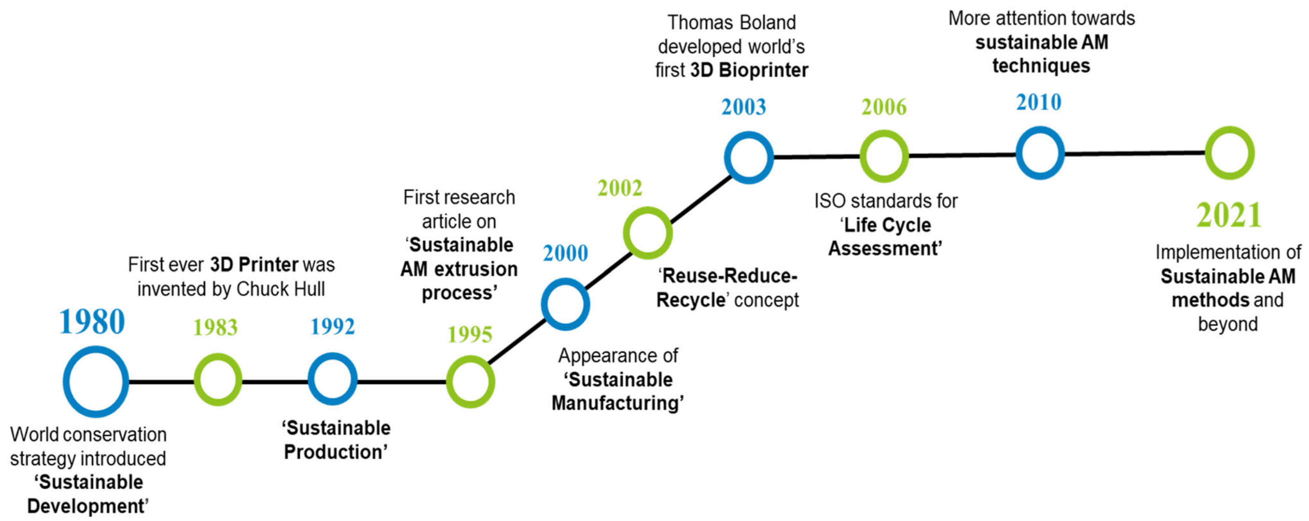
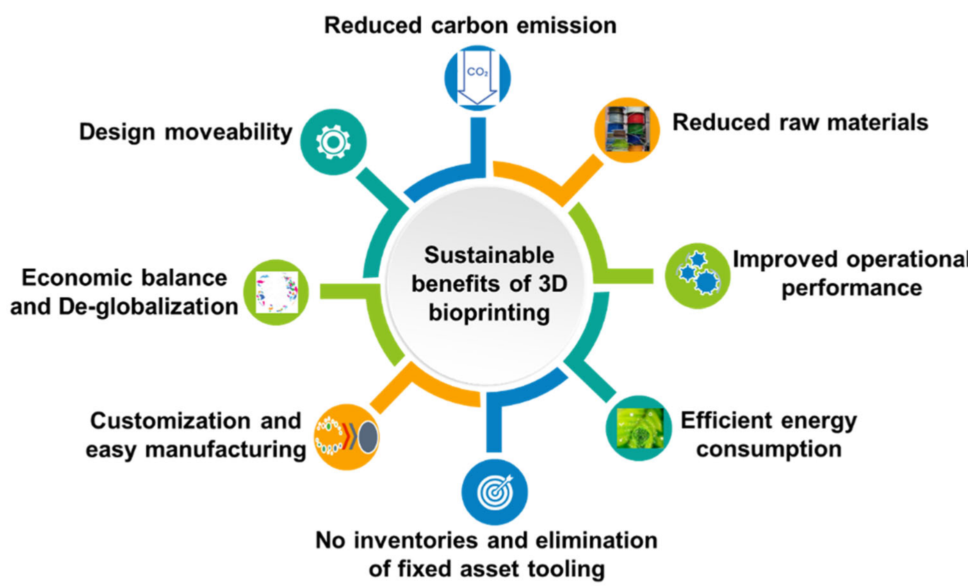


Fig. 1 Timeline of development sustainable additive manufacturing (AM) techniques

Fig. 2 Sustainable benefits of 3D printing over conventional manufacturing design



Bioprinting: a way toward sustainable and circular economy

3D bioprinting is a unique platform in the additive manufacturing sector for creating complex biology-based objects that mimic natural biological components. 3D bioprinting has shown a commendable capability for constructing structures such as tissues, cancer tumor models, cartilage and bone, and implants using a wide range of biomaterials such as natural polymers, synthetic polymers, cell-laden hydrogels, and bioinks [16]. Bioprinting can be classified by the methods of creating soft/hard tissues such as extrusion-based bioprinting, inkjet-based bioprinting, stereolithography-based bioprinting, and laser-assisted bioprinting. Extrusion-based bioprinting includes pneumatic, piston-driven, and screw-driven dispensing. Inkjet-based bioprinting is used for depositing a small volume of cell-laden constructs and biomaterials such as hydrogel, polymers, and small molecules with precise control over shape fidelity. Resins and photopolymers are widely used materials in stereolithography-based bioprinting (VAT photopolymerization, digital light processing (DLP)), especially for crosslinking the bioinks. Laser-assisted bioprinting is widely used for printing metals, synthetic polymers, ceramics, and composites [17]. Scopus search results of literature from 2010 to 2020 show that extrusion-based bioprinting has primarily used biofabrication techniques to create bone scaffolds, with other widely used techniques including inkjet-based bioprinting, laser-assisted bioprinting, and stereolithography-based bioprinting [18]. According to regional and segment forecasts, the 2020

Table 1 Sustainability dimensions in 3D bioprinting systems [26–28]

Dimensions of sustainability	Criteria
Economic	Reduced public health costs
	Increased market acceptance
	Positive economic impact
	Reduced production cost
	Reduced medical cost
	Machinery cost
Environmental	Minimized negative environmental impacts
	Utilization of sustainable materials
	Process and life cycle energy
	Improved waste management
	Decreased emission of indoor pollutants and greenhouse gases
Social	Higher quality of life
	Ethical framework
	Cruelty-free
	Improvements in health care
	Social acceptance
	Copyright and patents
Technical (Bioprinting)	Degrees of freedom
	Adoption of green materials for printing
	Optimized path planning algorithm
	Design optimization using part consolidation, lightweight consideration and topology optimization
	Support-structure optimization
	Small batch production
	Shorter product life cycle
	Recycling and remanufacturing

global 3D bioprinting market for medical and healthcare sectors is estimated to be around 1.4 billion USD and is expected to increase at a compound annual growth rate of 15.8% from 2021 to 2028 [19].

Apart from fabricating implants and tissues, the 3D bioprinting industry is also investing in 3D food production. According to FAO (Food and Agriculture Organization of the United Nations), global livestock contributes to 14.5% of greenhouse gas emissions and utilizes around 8% of freshwater resources. Cultured meat (CM), which produces meat sustainably through in vitro culture of animal cells without sacrificing animal life, is an emerging sustainable meat product, with the potential to meet the ever-increasing global meat demand for reduction of nutrition-related diseases and foodborne illnesses [20]. From 2015 to 2020, about 320 million USD has been invested by CM industries for livestock production. Reflecting growing interest in this approach, CM investments reached 161 million USD in 2020 alone [21].

3D bioprinting methods are known for their high "buy-to-fly" ratio, which is defined as the ratio of the mass of starting material to the mass of the finished product. The expanding build volumes can help in making 3D bioprinting technology feasible for small-batch production, thereby also increasing its efficiency. In adopting principles of sustainability, 3D bioprinting demonstrates several benefits (Fig. 2): optimized utilization of energy and raw materials, optimization of design and short supply-production chains, minimization of post-printing procedures, shape consolidation in a single step, and optimized multi-material processing time [22]. The social, economic, environmental, and technical dimensions of sustainability in 3D bioprinting systems are illustrated in Table 1. 3D bioprinting processing techniques can provide sustainable solutions by promoting a circular economy, which is defined in two ways: by recurrent use of biological nutrients that are present in the biosphere and by use of technical components that are designed to recycle at high efficiency without entering the biosphere [23]. Several factors need to be considered while selecting a particular manufacturing approach, including the associated costs of the process, material waste, and rates of energy consumption. A circular economy seeks to rebuild capital and enhance the flow of goods and services. Bioprinting can make significant reductions in material costs and increased realization of a circular economy in terms of maintenance, recycling, and remanufacturing of products and goods [24]. For instance, starch can be obtained for bioprinting even from waste streams in the potato processing industry (15 kg of starch-rich waste can be extracted from 100 kg of potatoes) [25]. Further, shortened supply chains and reductions in materials can lower production and transportation costs.

Sustainable materials for 3D bioprinting

A sustainable environment can be facilitated by use of biodegradable and recyclable polymers. The polymers currently used in 3D bioprinting are mostly byproducts from petrochemical industries. An approximately 80% turnover can be achieved just by printing polymers in AM for various applications. These synthetic polymers can cause severe damage to the ecosystem [29]: About 6.4 million tons of plastic are dumped into the ocean every year, causing the death of more than one million seabirds and 100,000 marine mammals annually. The extremely slow degradation rate of synthetic polymers exacerbates the environmental pollution even further. The present necessity is to replace these synthetic polymers with sustainable biopolymers [30], to achieve a balance between environmental health, climate change, and sustainable development. The constant demand for sustainable next-generation materials has also created more opportunities for AM techniques. Biopolymers derived from plants, microbes, and other organisms can be an ideal, more sustainable alternative to their synthetic counterparts [30]. For instance, starch-derived polymers such as PLA (polylactic acid), PHB (poly-hydroxybutyrate), and PHA (polyhydroxyalkanoates), derived from wheat, maize, potato, and cassava processed through bioprinting offer potential environmental benefits by reducing the carbon footprint of the manufacturing process. These biopolymers generate fewer volatile by-products and pollutants than synthetic petroleum-based polymers, with greater sustainability [31].

Alginate, a natural polymer derived from marine plants and bacteria, is used as a hydrogel in the biofabrication process. It has strong mechanical properties that are ideal for biofabrication. Alginate has been combined with nanocellulose for use as a bioink to assess its biocompatibility with human nasoseptal chondrocytes. This composite material was printed using an extrusion-based 3D bioprinter with optimized process parameters. The alginate-nanocellulose bioink product demonstrated shape fidelity (reversible stress softening behavior), a high degree of shear thinning, and a stable build volume. Bioink hydrogels formulated from pectin (a polysaccharide found in the middle lamella of plant cells) by crosslinking with GPTMS ((3-Glycidyloxypropyl) tri-methoxy-silane) is a novel and versatile biomaterial that shows good viscosity, yield stress and cytocompatibility characteristics [32, 33].

Lignin, a biomass material from industrial feedstock waste, has been combined with synthetic polymers such as acrylonitrile–butadiene–styrene (ABS) and nylon on a 40:60 weight ratio to increase manufacturing sustainability. The lignin-based biocomposite, produced by an extrusion-based AM technology, fused deposition modeling (FDM), exhibits greater tensile strength and stiffness at room temperature. Sustainable vascularized microtissues have been 3D printed as self-assembled lignin-containing components for use in soft tissue repair in vivo; lignin-based constructs have also been applied as sustainable in vitro disease models [34]. Lignocellulosic materials (cellulose, hemicellulose, and lignin) from various sources (wood, bacteria, and fungi) can be used in 3D bioprinting as nanofiber or nanocrystals as they are sustainable biomaterials with tunable mechanical properties and biocompatibility. Lignocellulosic materials are widely used in tissue engineering, wound dressing applications, and as skin tissue mimics [35]. Cellulose-based nanofibers (CNF) are promising sustainable materials for hydrogels, which exhibit excellent biocompatibility, mechanical performance, adequate compressive strength, and elasticity; these hydrogels also show potential for use as elastic hydrogels. Affordable patient-specific scaffolds that mimic different tissues can be biofabricated by 3D bioprinters using cellulose without supporting structures [36]. The various sustainable materials derived from nature and processed by 3D bioprinting are illustrated in Fig. 3.

Bioinspired structures and product designs

The unique combination of design and superior properties of biomaterials is employed in various engineering systems to meet certain functional requirements. Biological design, or ecological design, enables minimal use of materials to create an ecologically sustainable manufacturing process. The distinctive characteristics of biological structures, such as hierarchical organization, multi-functionality, self-healing, self-assembly, and enhanced physical characteristics, ensure savings in time, materials, and energy in manufacturing. Bioinspired structures such as sutures, gradients, interlocks, cross-lamellae, and honeycombs are being considered for AM-based bioprinting applications [37, 38]. In addition to freeform design (customized design), simulation-driven design and lattice design approaches are used in design of AM fabricated components with varying levels of biological input or bioinspiration [39]. Minimizing the weight of materials while maintaining the maximum strength in honeycomb structures has proved to be an excellent innovation in the field of composite structures. 3D-printed, evaluation of ABS-composite honeycomb structures using FTIR (Fourier Transform Infrared Spectroscopy) characterization and impact analysis indicated that 3D printed multilayered,

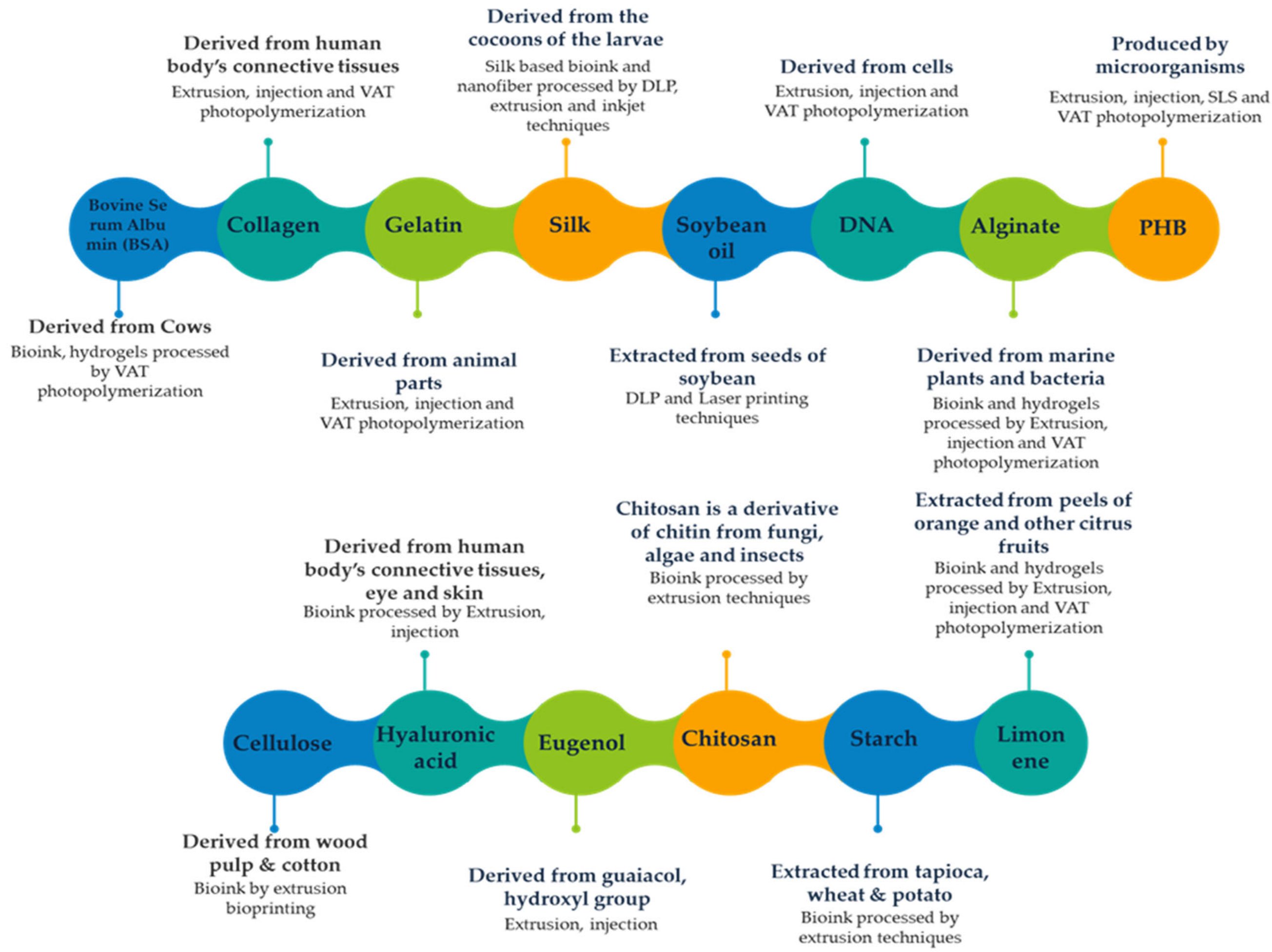


Fig. 3 Naturally derived sustainable materials used in 3D bioprinting techniques

fabric-sandwiched honeycomb composite structures have potential mechanical applications in the mass transport and avionics sectors [40]. The bioinspired structures proved to be a better option for these uses because of their light weight and efficient fuel consumption; manufacture of these structures also requires less raw materials than conventional materials, and it also reduces the carbon footprint [41].

From a nanoscale level to centimeter-scale level, human bones are composed of collagen fibrils, mineral platelets, and osteons. This hierarchical arrangement of bone architecture helps bones to move around and work with enhanced stiffness and toughness [37]. The design of a cranial prosthesis created using a generative design approach is called a Voronoi diagram or tessellation. Using this approach, a customized, patient-specific cranial implant was designed by mimicking bone trabeculae to repair cranial defects [42]. Lightweight titanium alloys have been fabricated using laser-based AM approach, selective laser melting (SLM), and a thermoset polymer resin was processed by digital light processing for cortical bone applications [43]. Direct ink writing (DIW) is an AM approach used to construct viscoelastic ink using hydroxyapatite, layer by layer, for engineered bone applications [44]. Table 2 depicts various bioinspired structures and bioprinting methods using suitable biomaterials for various biomedical applications.

Energy sustainability in 3D bioprinting

Life-cycle inventory of various bioprinting techniques indicates the usefulness of precise machine tools as a suitable eco-friendly material to consume less energy in manufacture. Laser-assisted bioprinting consumes more energy than all other bioprinting techniques. Powder feed and preheating require 40% of system's energy; 16% is spent on operation of the laser system, and 25% is spent on feeding and building piston stepper motors [48, 49]. To save energy and reduce carbon emissions, a better thermal management system replacing lasers, such as selective heat sintering (SHS), selective mask sintering (SMS), and selective inhibition sintering (SIS), needs to be introduced to 3D bioprinting techniques. Even though these alternate systems still use thermal

Table 2 Bioinspired structures used in biomedical applications [15, 45–47]

Bioinspired structure	3D bioprinting technique	Biomaterials	Biomedical application	Enhanced characteristics
Hollow tubular structures	Extrusion-based bioprinting	Polyethylene glycol (PEG) derivatives mixed with fibroblasts	Vascular constructs	Biocompatible
Bioinspired interface structures	Stereolithography-based bioprinting	polyethylene glycol (PEG)/β-tricalcium phosphate (β-TCP) scaffold	Cartilage—Bone	Biocompatible
Tubular structures	4D bioprinting	Gelatin- polycaprolactone (PCL)	Bilayers, cell-laden bioscaffolds for tissue engineering	Compatible; Biodegradable
Native stiff bone-like constructs	3D bioprinting	Polyglycolic acid/polylactic acid (PLA/PGA) scaffolds	Cartilage—bone	Biocompatible, stiffness
Bioinspired lattice structures	Laser-assisted bioprinting	Functionally graded Inconel 718 superalloy	Hip implant	Stronger, enhanced load-carrying ability
Helicoidal structure inspired by mantis shrimp	Near-field electrospinning technique (NFES)—a micro-AM technique	polycaprolactone (PCL)/polyvinylidene fluoride (PVF)	Bone implants	High load-carrying capacity and better crack and delamination resistance
Bioinspired cellular structures	Stereolithography-based bioprinting	Photopolymerizable polymer (composed of urethane acrylate oligomers)	Bone biomimetic implants	Balanced mechanical and biological properties
Biomimicking native tissue	3D bioprinting	Chitosan-HAP (hydroxyapatite)	Hydrogel, scaffolds, bone tissue engineering	Biocompatible, cell viability, cell-friendly environment, adequate mechanical properties
	Extrusion-based bioprinting	Collagen, gelatin, alginate, silk fibroin	Bioink, hydrogel	Good mechanical properties, biodegradable, cell viability
	Inkjet-based bioprinting	Fibrin ink	Vascular constructs	Cell proliferation and microvasculature formation

energy for efficient energy consumption, their use is limited to polyamide materials only [50]. In AM techniques, product design can be simplified through part consolidation, resulting in a lightweight structure, enhanced performance, and prolonged service life. A framework known as generic quantitative models can be used to systematically investigate the sustainability potential of part consolidation; this assessment indicated that part consolidation design has a significant effect on sustainability, reducing energy consumption and environmental impact by 20% [51, 52].

Another new concept introduced by researchers to reduce consumption of materials and electricity is using Design for Sustainable Additive Manufacturing (DFSAM) approach, which are predictive models for sustainable manufacturing to minimize negative environmental impacts. One AM machine manufacturer, EOS, has followed the "cut material consumption" principle to lessen environmental impact; this approach reduced the materials consumption rate by 75%, which resulted in reduction of CO_2 emissions by 40% [48]. The energy consumption and environmental analysis of various bioprinting techniques are summarized alternative to lasers in Table 3. Analysis of these methods for feedstock production indicated that there was still only limited data to evaluate their impact on direct and indirect emissions [53].

Specific energy consumption (SEC) of bioprinting techniques is calculated as energy consumption per unit deposition volume. The average applied energy per unit volume of bioprinted parts during the layered deposition process is shown in Eq. (1):

$$\mathrm{SEC} = PT/V, \tag{1}$$

where P is input power (in W or kW), T is processing time (in seconds), and V is the volume of the deposited object (in cm^3). The carbon footprint for bioprinting techniques is given by Eq. (2):

Table 3 Life cycle inventory (LCI) of bioprinting techniques

Bioprinting technique	Machine tool	Material	Average operational power (kW) range	Specific energy consumption (SEC) range	Carbon footprint	Reference
Laser assisted bioprinting technique						
Selective laser sintering (SLS)	DTM sinterstation	Polymers	12.500–16.800	107.4–144.3	1.1 ($kgCO_2$-eq/kg)	[54, 55]
	EOSINT	PA powders	2.920–6.610	107.0–145.1	6.7–6.9 ($kgCO_2$-eq/kg)	[56, 57]
	3D-Systems HiQ + HiS	PA 12	5.500	130.0	6.9 ($kgCO_2$-eq/kg)	[58]
SLM	Concept laser	316L	1.090–3.350	83.0–588.0	0.44 ($tonCO_2$)/ (t on SS)	[49]
		Aluminum	0.790	309.1–533.0	8.96 ($kgCO_2$-eq/kg)	[59]
	MTT SLM	316L	1.090	83.0–108.0	0.44 ($tonCO_2$)/ (ton SS)	[49]
	Renishaw	$AlSi_{10}Mg$	1.166	566.2	N.A	[60]
Direct metals laser sintering (DMLS)	LUMEX 25 DMLS	316L	3.6	204.4–470	1.95 ($kgCO_2$-eq/kg)	[61]
Laser direct deposition (LDD)	Laserline, GmbH	316L	2	1052	9.33×10^{-2} ($kgCO_2$-eq/kg)	[62]
Extrusion based bioprinting technique						
FDM	Stratasys FDM	ABS	1.320–11.000	83.1–1247.0	0.34 ($kgCO_2$-eq/kg) (NRE)	[54, 63]
					0.17 ($kgCO_2$-eq/kg) (RE)	
		PC	2.450	519.0–536.0	3.04×10^{-1} ($kgCO_2$-eq/kg)	[49, 64]
Stereolithography based bioprinting technique						
Stereolithography (SLA)	3D systems SLA	SL 5170	1.200–3.000	74.5–116.9	1.36×10^{-1}($kgCO_2$-eq/kg)	[54, 65]
Inkjet based bioprinting technique						
Multi jet fusion (MJF)	HP Jet Fusion 4210	PA 12	8.525	98.69–152.54	1 Kg of PA 12 produces 45.8 ($kgCO_2$-eq/kg)	[66]
Other bioprinting technique						
Electron beam melting (EBM)	Arcam	Ti_6Al_4	2.133–2.220	61.0–375.0	0.43–1.12 ($kgCO_2$-eq/kg)	[67]
		316L		528.90–560.60	9.85–20.68 ($kgCO_2$-eq/kg)	[49, 68]

NRE: non-renewable electricity; RE: renewable electricity; N.A: not available

$$\text{Carbon footprint}\left[\text{KgCO}_2\right] = E_{\text{part}}\,[\text{GJ}] + \text{CESTM}\left[\text{KgCO}_2/\text{GJ}\right], \quad (2)$$

where E_{part} is the energy consumed for producing one part and CESTM is the carbon emission signature calculated for the energy mix at a particular year and a particular country [63]. While developing sustainable practices in bioprinting, the interaction between SEC of bioprinting machine tools and materials should be thoroughly investigated, as it may have environmental impacts such as carbon emissions. SEC of bioprinting techniques is influenced not only by the choice of processing materials but also by the specific process parameters chosen for processing them. For example, the laser-assisted bioprinting technique known as “LENS” requires higher energy density with smaller powder size and layer thickness. Higher energy density causes higher SEC which has to be minimized to maintain energy efficiency and to reduce carbon emissions [65].

Table 4 Potential applications of sustainable 3D bioprinting applications

Potential applications	Bioprinting techniques	Materials/Structure	Sustainable features	Reference
Nutritional applications: cultured meat (synthetic meat); food printing; nutraceuticals and health supplements	Extrusion-based bioprinting, inkjet-based bioprinting binder jetting, chocolate-based ink 3D printing (Ci3DP), milk-based 3D printing	Insects, animal byproducts, plant-based ingredients, fresh vegetables, milk-based products	Reduction in food waste, sustainable food development, use of alternative sources of protein, enhanced nutritional benefits for targeted public in order to improve health benefits, improved dietary practices, reduced energy consumption and carbon emission	[20, 70–76]
Pharmacological applications: patient-specific drug delivery and screening	3D bioprinting	Gelatin and sodium alginate mixed with hepatorganoids with HepaRG cells, biopolymers	Drugs for personalized treatment of hepatocellular carcinoma (HCC) liver cancer, with biopolymers which reduce carbon emission	[77, 78]
Tissue engineering applications	Laser-assisted bioprinting, extrusion-based bioprinting, inkjet-based bioprinting	Naturally derived polymers, native cells, mimicking native tissues, bioinks	Possibility of producing artificial tissues (soft tissues and hard tissues), customized patient-specific therapies with enhanced biological and mechanical properties, reduced usage of synthetic materials and energy consumption	[9, 16, 78, 79]
Regenerative medicine: For human space exploration and planet colonization	Extrusion-based bioprinting, inkjet-based bioprinting	Biobased products	Stimulates space research and technology development, self-sustainable mission	[80]

Conclusions and future prospects

Biomaterials and bioinspired structures play a significant role in the development of sustainable 3D bioprinting practices. Deriving biomaterials from renewable resources and processing them through 3D bioprinting is challenging in many ways [9]. This perspective highlights the correlation between bioprinting factors and the socio-economic and environmental aspects of sustainable production by focusing on biomaterials and bioinspired structures [30]. This focus helps researchers to assess whether 3D bioprinting can meet the needs of environmental sustainability by using naturally derived materials, recyclable materials, and renewable energy sources [69]. Table 4 lists some potential applications of sustainable 3D bioprinting.

Despite the potential of 3D bioprinting in the above applications, there are still challenges and barriers to large-scale production. Bioprinting has yet to adopt a wide range of nature-derived materials as it has limited to use of certain classes of materials. Polysaccharides, a natural resource derived from plant, fungi, and marine organisms, offer important potential for savings in non-renewable energy use (NREU) and greenhouse gas (GHG) emissions. Sustainable 3D bioprinting also shows immense potential for meeting the growing demand for engineered tissues and high-quality foods with low manufacturing costs. Polysaccharide-based end products should be utilized more in 3D bioprinting to improve significant environmental benefits [81].

The application of the 3R principle (reduce-reuse-recycle) to bioprinting can facilitate effective material utilization [31]. Further, increasing the degrees of freedom of bioprinting techniques paves a way for development of new, more sustainable methods and materials. Renewable energy sources help to improve and reduce the environmental impact of 3D bioprinting. Life-cycle assessment tools can improve the sustainability effects of bioprinting by creating a positive impact on the social, economic, and environmental aspects [82]. A sustainable future can be ensured by improving government policies, industrial norms, and public opinion. As responsible citizens, everyone must work to protect the planet from the adverse effects of climate change, exhaustion of natural reserves, and disruption of ecological balance.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This study does not contain any studies with human or animal subjects performed by any of the authors.

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