STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810
Volume 12, Issue 5, 2024
DOI (Journal) 10.37591/JoPC

http://engineeringjournals.stmjournals.in/index.php/JoPC/index

Review JoPC

Eco-Friendly Innovations: A Review of 3D Printing with Biodegradable Filaments

Preeti Bansal[1,] *, Simarpreet kaur[2], Nidhi Chahal[3], Tarun Singhal[4],Vivek Singh Manola[5]

Abstract

This comprehensive review paper delves into the evolving landscape of sustainable additive manufacturing, focusing on the utilization of biodegradable filaments in 3D printing technology. As industries increasingly prioritize sustainability, the adoption of eco-friendly practices like biodegradable materials becomes imperative. The study explores the composition and properties of biodegradable filaments, highlighting their transformation from traditional plastic fibres and the environmental benefits they offer. With a particular emphasis on fused deposition modeling (FDM) technology, the review elucidates how biodegradable polymers are seamlessly integrated into the additive manufacturing process. By depositing melted material layer by layer, FDM enables the creation of objects with reduced environmental impact. Materials such as Polyhydroxyalkanoates (PHA), Polylactic acid (PLA), and High-impact polystyrene (HIPS) are discussed as examples of biodegradable components that mimic the properties of conventional plastics while being environmentally friendly. Furthermore, the review explores the diverse array of applications enabled by the intersection of biodegradable polymers and FDM, spanning various sectors. From manufacturing to healthcare, these applications underscore the versatility and potential of 3D-printed biodegradable materials in driving sustainable innovation. Through meticulous examination of current trends and emerging technologies, the review aims to provide valuable insights for researchers, practitioners, and enthusiasts eager to explore the promising landscape of sustainable 3D printing. By presenting a comprehensive overview and distilling key insights, it seeks to contribute to a deeper understanding of the sustainable possibilities within the field of additive manufacturing.

Keywords: -Sustainability, biodegradable filaments, additive manufacturing, fused deposition modelling (FDM), environmental impact

INTRODUCTION

The rise of 3D printing has transformed manufacturing processes, and the integration of biodegradable filaments marks a significant step towards environmentally responsible practices. This review examines the composition, characteristics, and applications of biodegradable filaments in 3D printing, focusing on their potential to reduce environmental impact [1]. In the dynamic landscape of additive manufacturing, the fusion of technology and sustainability has given rise to a ground-breaking innovation—3D printing with biodegradable filaments. As the environmental impact of traditional plastics comes under scrutiny, the quest for eco-friendly alternatives has become paramount. Biodegradable filaments offer a compelling solution, revolutionizing the field of 3D printing by addressing ecological concerns while maintaining the versatility and precision that additive manufacturing is renowned for [5]. The

***Author for Correspondence**
Preeti Bansal

[1-3]Assistant Professor, Department of Electronics and Communication Engineering, CEC, CGC, Landran, Mohali, Punjab, India
[4]Associate Professor, Department of Electronics and Communication Engineering, CEC, CGC, Landran, Mohali, Punjab, India
[5]Student, Department of Electronics and Communication Engineering, CEC, CGC, Landran, Mohali, Punjab, India

Received Date: February 05, 2024
Accepted Date: July 30, 2024
Published Date: July 30, 2024

Citation: Preeti Bansal, Simarpreet kaur, Nidhi Chahal, Tarun Singhal, Vivek Singh Manola. Eco-Friendly Innovations: A Review of 3D Printing with Biodegradable Filaments. Journal of Polymer & Composites. 2024; 12(5):86 –102p.

advent of 3D printing, also known as additive manufacturing, has heralded a new era in the production of intricate and customized objects across diverse industries. Traditional filaments, primarily derived from non-renewable resources, have raised environmental challenges due to their persistence in landfills and ecosystems. In response to these concerns, researchers and innovators have turned to biodegradable materials as a sustainable alternative, laying the foundation for a more responsible approach to 3D printing. Biodegradable filaments are typically crafted from renewable resources such as plant-based polymers, presenting a departure from the fossil fuel-based plastics commonly used in traditional additive manufacturing [7]. The utilization of bio-based materials not only addresses the issue of resource depletion but also introduces the inherent ability of these filaments to break down naturally over time. This review explores the intricate interplay between 3D printing technology and biodegradable filaments, examining their composition, advantages, challenges, and burgeoning applications. From the inception of biodegradable filaments as a concept to their integration into diverse sectors such as consumer goods, medical applications, and education, this exploration aims to provide a comprehensive understanding of the evolving landscape of sustainable additive manufacturing [11]. As we navigate the intricate world of 3D printing with biodegradable filaments, it becomes evident that this intersection of technology and eco-consciousness holds the promise of transformative change. The subsequent sections delve into the unique properties of these filaments, shedding light on their environmental benefits, challenges faced in their utilization, and the exciting potential they hold for shaping a more sustainable future in the realm of additive manufacturing.

MATERIALS OF BIODEGRADABLE FILAMENTS

Biodegradable filaments are typically derived from renewable resources such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), and other bio-based polymers. These materials offer a sustainable alternative to traditional petroleum-based plastics, providing a pathway to reducing carbon footprints associated with additive manufacturing. The composition of biodegradable filament for 3D printing primarily revolves around the use of renewable and bio-based materials. The goal is to create a sustainable alternative to traditional filaments, often derived from non-renewable fossil fuels [6]. Various bio-based polymers contribute to the composition of biodegradable filaments, providing a diverse range of options for environmentally conscious additive manufacturing. Here are some common materials used in the composition of biodegradable filaments. The properties of these materials are summarized in Table 1:

Table 1. Properties of materials.

Material	Produced from Produced from Produced from	Properties	Extrusion temperature Extrusion temperature	pros	cons
PLA	Plants starch	Tough, Strong	160 ÷222°C	Bio-plastic, on-toxic, odourless, low-wrap	Low heat resistance, brittle
PVA	Petroleum	Water-soluble, good barrier	190÷210°C	Biodegradable,recyclable, non-toxiBiodegradable, recyclable,non-toxic	Expensive, deteriorates with moisture, special storage
PHA	Sugars with biosynthesis	Several copolymers, brittle and stiff	~160°C	UV-stable, stiffness	Elasticity, brittle
HIPS	Petroleum	High impact resistance, soluble in limonene	190÷210°C	Biodegradable, low cost, similar to abs	Warping, heated printed bed
PET	Petroleum	Strong and Flexible	210÷230°C	FDA approved, Recyclable	Absorbs moistness

Polylactic Acid (PLA): Figure. No. 1

PLA is one of the most widely used bio-based polymers for biodegradable filaments. It is derived from renewable resources such as corn starch or kenaf or sugarcane. PLA has gained popularity in 3D printing due to its biodegradability, low environmental impact, and ease of use. PLA filaments are suitable for a range of applications, from prototyping to consumer goods.[2] PLA is known for being eco-friendly because it can break down into harmless substances like carbon dioxide and water when composted in the right conditions. However, its ability to compost depends on factors like temperature, humidity, and the presence of microbes. Apart from being biodegradable, PLA has other good qualities like being see-through, sturdy, and resistant to heat, making it useful for many different purposes. But it does have drawbacks too, like not being great at handling low temperatures and being prone to breaking down in certain environments [7]. PLA has become more popular lately because people are interested in using materials that are better for the environment, and it's often used instead of regular plastics made from oil. This helps with making manufacturing and packaging more sustainable and eco-friendly.

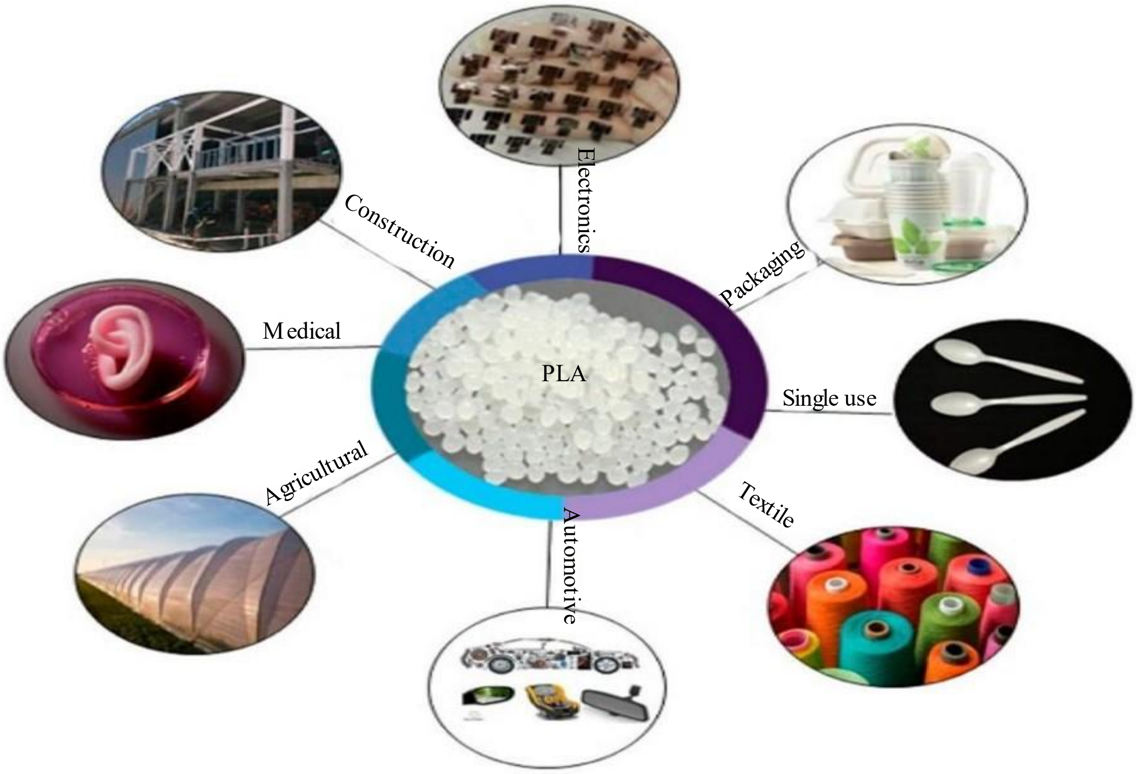

Figure 1. Polylactic acid [16].

Polyhydroxyalkanoates (PHA): Figure. No. 2

PHA is a family of bio-based polymers produced by microorganisms. These polymers are biodegradable and can be derived from renewable resources like plant oils or agricultural waste. PHA filaments offer good mechanical properties and are being explored for various applications, including packaging and biomedical uses. Polyhydroxyalkanoates (PHAs) are a group of biodegradable polymers produced naturally by certain bacteria as a means of storing carbon and energy. They are considered environmentally friendly because they can be broken down by microorganisms into harmless by-products like carbon dioxide and water under the right conditions. PHAs have gained attention as sustainable alternatives to conventional plastics derived from fossil fuels [1]. These biopolymers have various properties depending on their composition, including flexibility, strength, and biocompatibility, making them suitable for a wide range of applications such as packaging, medical devices, and agricultural materials. Researchers and industries are actively exploring ways to improve PHA production processes and expand their use to contribute to a more sustainable future [4].

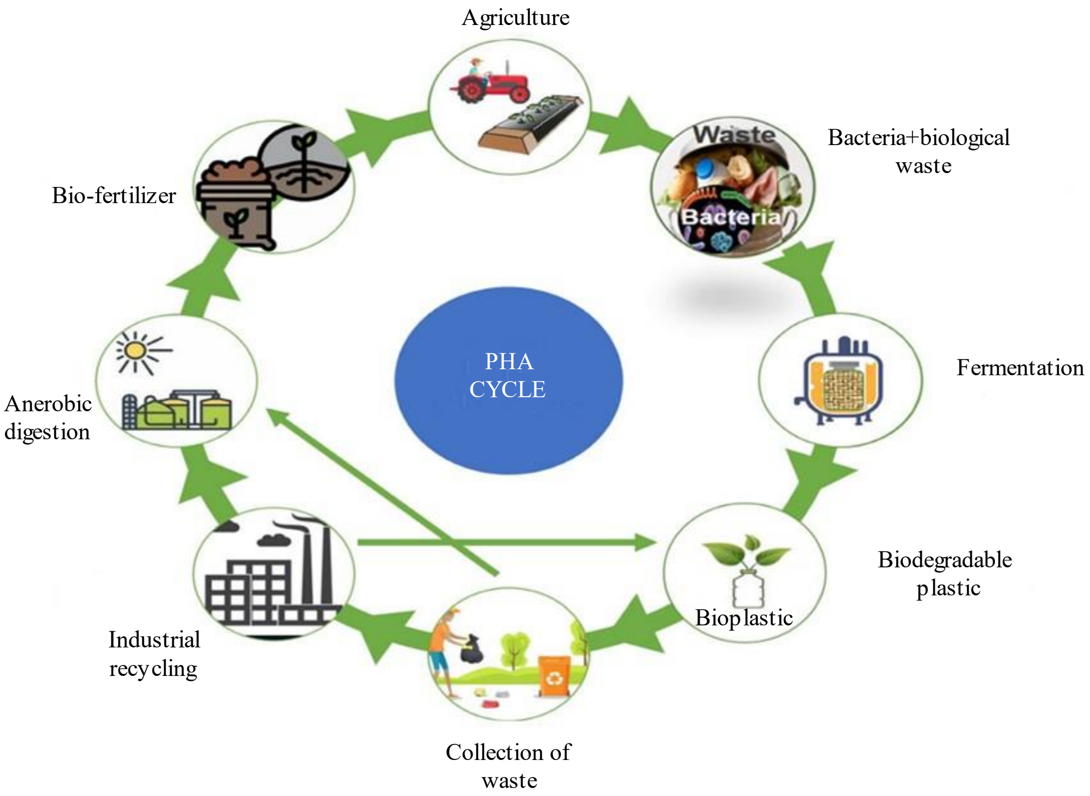

Figure 2. Polyhydroxyalkanoates [17].

Polycaprolactone (PCL): Figure. No. 3

PCL is a semi-crystalline polyester that is biodegradable and derived from petrochemicals. While it may not be plant-based, PCL is considered biodegradable under certain conditions. PCL filaments have a lower melting point, making them suitable for applications such as custom medical implants and prototyping. Polycaprolactone (PCL) is a type of plastic that is easy to shape because it melts at a low temperature. It's made from certain motes combined in a process called ring-opening polymerization. PCL is known for being really handy and safe to use in all feathers of effects, like drug, packaging, and 3D printing [3]. One of the cool effects about PCL is that it breaks down sluggishly over time, so it can stay strong for quite a while. This makes it perfect for effects like special medicine delivery systems or frames for growing apkins. It's also flexible, safe, and can be mixed with other plastics, which makes it a popular choice for making effects that need to break down naturally. People like using PCL because it's better for the terrain than regular plastics made from oil painting. It's used in medical stuff like aches and implants, as well as in packaging and 3D printing. Since it breaks down naturally and works well in different ways of making effects, it's getting more and more popular for making stuff that is better for the earth [8].

TPI (Thermoplastic Starch): Figure No. 4

TPI filaments are composed of a blend of thermoplastic polymers and starch. Starch is derived from crops like corn or potatoes, providing a renewable component. These filaments often exhibit good biodegradability and can be used for various applications, including packaging and disposable items. Thermoplastic starch (TPS) is a biodegradable polymer derived from renewable resources such as corn, wheat, potatoes, and other starch-rich crops.[14] It is a type of bioplastic that has gained attention due to its biodegradability, renewability, and potential as an alternative to traditional petroleum-based plastics. TPS is produced by processing starch, usually corn or potato starch, with plasticizers and sometimes other additives such as glycerol or water. The starch molecules are heated and then processed into a plastic-like material that can be moulded into various shapes using conventional plastic processing techniques such as extrusion, injection moulding, or compression moulding. One of the main advantages of TPS is its biodegradability.[11] Unlike conventional plastics, which can persist in the environment for hundreds of years, TPS can be broken down by microorganisms into simpler compounds, such as carbon dioxide and water, within a relatively short period of time under suitable conditions. This makes TPS an attractive option for applications where biodegradability is important, such as packaging and single-use disposable items [11].

Figure 3. Polycaprolactone.

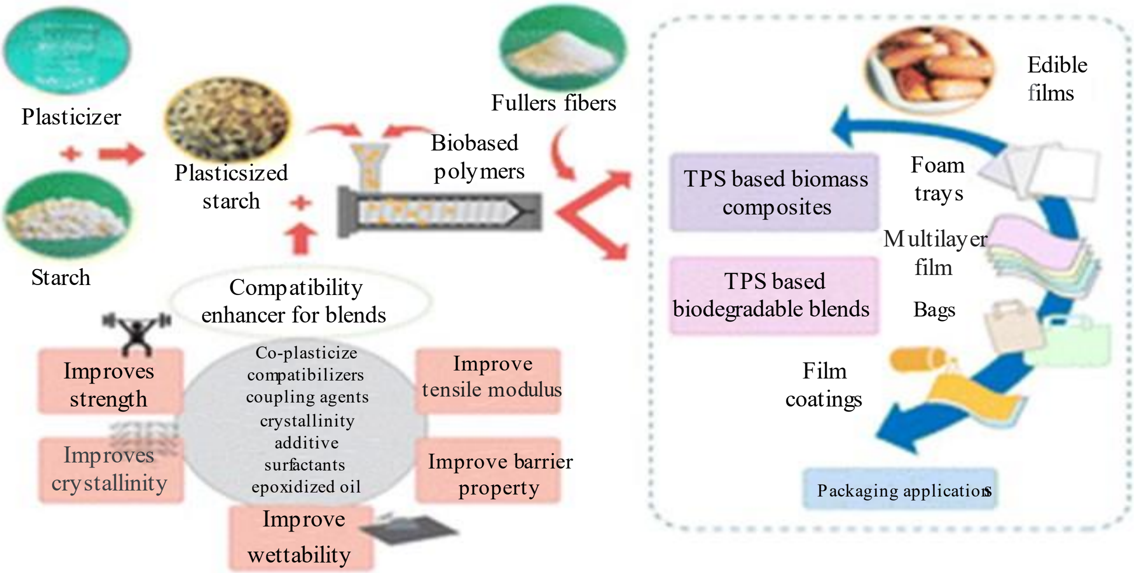

Figure 4. Thermoplastic starch [18].

PBS (Polybutylene Succinate): Figure No. 5

PBS is a bio-based polyester that can be used as a component in biodegradable filaments. It is derived from succinic acid, which can be obtained from renewable feedstock. PBS filaments offer good mechanical properties and are explored for applications in agriculture and packaging. Polybutylene succinate (PBS) is a type of biodegradable thermoplastic polyester formed from succinic acid and 1, 4-butanediol [2]. It's gaining attention for its potential in various applications due to its ability to degrade naturally, its mechanical strength, and its ease of processing. To make PBS, succinic acid and 1,4-

butanediol undergo a condensation polymerization reaction, forming a polymer chain comprising butylene succinate units. This polymer can then be shaped using standard plastic processing methods like extrusion, injection moulding, or blow moulding, making it versatile for many uses. One of the main advantages of PBS is its ability to biodegrade. Given the right conditions, microorganisms can break down PBS into carbon dioxide, water, and biomass over time.[9] This makes PBS particularly appealing for applications where environmental impact is a concern, such as in packaging, agricultural films, disposable items, and mulch films. Furthermore, PBS boasts favourable mechanical properties, including high tensile strength, flexibility, and resistance to impact. It also remains stable at high temperatures during processing, ensuring its integrity is maintained. Overall, PBS presents a promising alternative to conventional plastics, especially in scenarios where biodegradability is a priority. Ongoing research aims to further improve its performance, cost-effectiveness, and potential applications, while also exploring alternative sources to avoid conflicts with food production [15].

Figure 5. Polybutylene [19].

Polyesters from Renewable Resources: Figure No. 6

Researchers are continually developing new bio-based polyesters from renewable resources, exploring plant oils, waste materials, and other sustainable feedstock. These emerging polymers contribute to the expanding range of biodegradable filament options. It’s important to note that the composition of biodegradable filaments can vary, and manufacturers may incorporate additional additives or blends to enhance specific properties such as strength, flexibility, or printability [5]. As the field of sustainable 3D printing evolves, ongoing research and innovations are likely to introduce new bio-based materials and improve the overall performance of biodegradable filaments.

PRINTING TECHNIQUES AND TECHNOLOGIES

1. *Fused deposition modelling (FDM) figure no. 7:* The process of creating three-dimensional items layer by layer is known as fused deposition modeling, or FDM. It is a widely used additive manufacturing technique. In this process, a thermoplastic filament, such as PLA or ABS, is fed into a heated nozzle where it melts into a semi-liquid state. The printer head, controlled by specialized software, moves along predetermined paths, precisely depositing the melted material onto a build platform. Each layer of material fuses with the previous one, gradually constructing the desired object. After deposition, the material quickly cools and solidifies. FDM printing is renowned for its affordability, accessibility, and versatility, making it widely employed across various industries for prototyping, rapid manufacturing, and end-use part production. While FDM-printed parts may exhibit visible layer lines and relatively lower resolution compared to

other methods, its ease of use and broad applicability continue to drive its popularity in the realm of additive manufacturing [10].
Principle: Extrudes thermoplastic filaments layer by layer to create the object
Materials: PLA, ABS, PETG, TPU, etc.
Applications: Prototyping, hobbyist projects, functional parts.

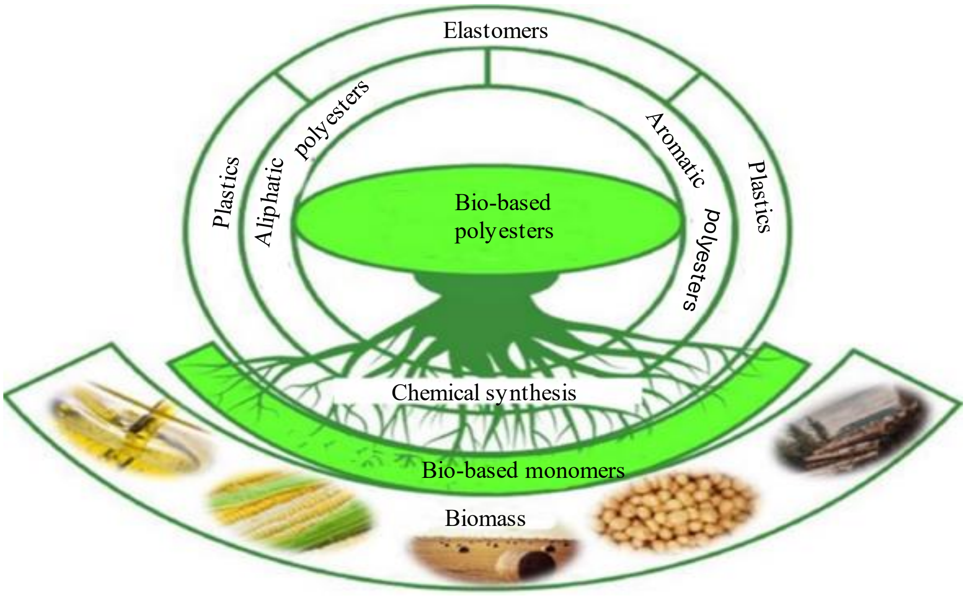

Figure 6. Polyesters from renewable resources [20].

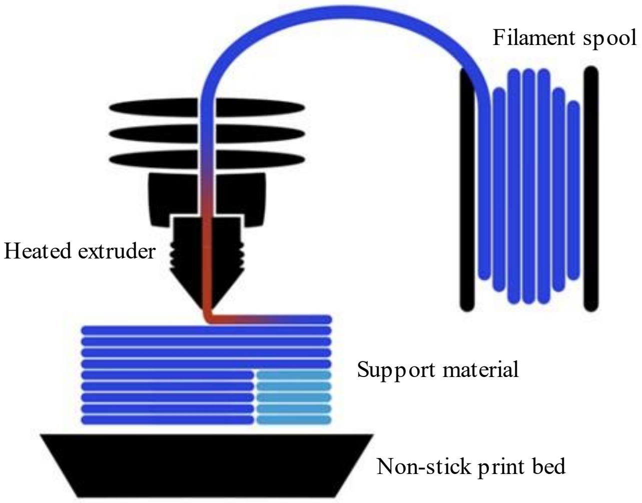

Figure 7. Fused deposition modelling.

2. *Stereolithography (SLA*): Figure. No. 8Using a liquid resin that has been cured by ultraviolet (UV) light, stereolithography (SLA) is an additive manufacturing technique that builds three-dimensional things layer by layer.
   It is one of the earliest and most widely used 3D printing technologies, particularly in industries requiring high precision and fine details. In stereolithography, a vat of liquid photopolymer resin is exposed to a UV laser beam, which selectively cures the resin, solidifying it into the desired shape corresponding to a cross-section of the object being printed. The build platform then moves downward, allowing for the next layer of resin to be exposed and cured. This process repeats until the entire object is formed. SLA offers several advantages, including high accuracy,

excellent surface finish, and the ability to produce intricate geometries and fine details that may be challenging with other 3D printing methods [12]. Additionally, SLA printers can produce parts with tight tolerances, making them suitable for various applications in industries such as aerospace, automotive, healthcare, and consumer products. However, SLA also has some limitations, such as limited material selection compared to other 3D printing processes and the requirement for post-processing to remove excess resin and cure the final part fully. Additionally, SLA printers tend to be more expensive and slower compared to some other 3D printing technologies. Overall, stereolithography remains a valuable and widely used additive manufacturing technique, particularly for applications where high precision, fine details, and excellent surface finish are paramount. Ongoing advancements in SLA technology continue to improve its capabilities and expand its range of applications across various industries.
Principle: Uses a UV laser to cure liquid resin layer by layer, creating high-resolution models.
Materials: Resin-based photopolymers.
Applications: High-detail prototypes, dental models, jewellery.

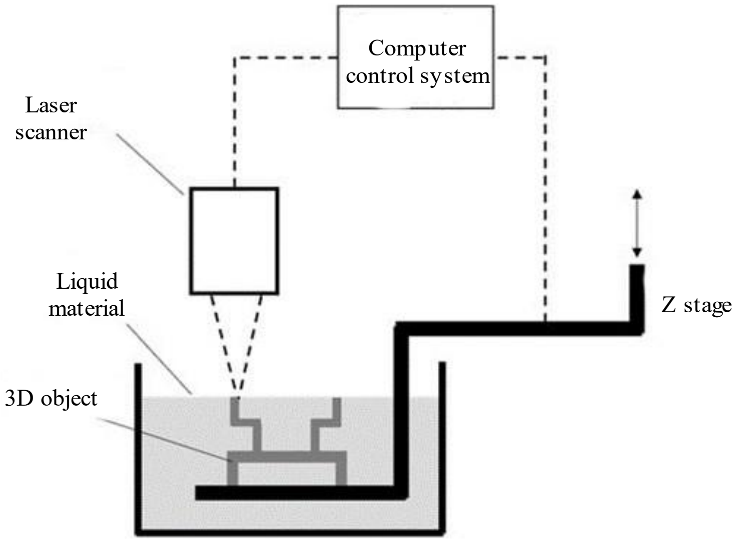

Figure 8. Stereolithography.

3. *Material jetting figure no. 9:* Material Jetting is an advanced additive manufacturing technique that revolutionizes the creation of three-dimensional objects by jetting droplets of material onto a build platform layer by layer. Resembling the principles of inkjet printing but utilizing photopolymer or wax-like materials, Material Jetting ensures precision and intricacy in fabrication. In this process, liquid material is precisely deposited onto the build platform through an array of nozzles, guided by digital design specifications. These droplets quickly solidify either through exposure to UV light or by controlled heating, forming a solid layer. The build platform then incrementally descends, and the process repeats, layer upon layer, until the complete object is formed. Material Jetting boasts remarkable advantages. It achieves high resolution, exceptional surface finish, and intricate details, making it ideal for industries like aerospace, automotive, jewellery, and healthcare. Moreover, it offers the versatility of producing multi-material or multicolour objects in a single print run. Despite its benefits, Material Jetting may face challenges such as slower printing speeds and higher material costs. Additionally, post-processing may be necessary to remove support structures and refine surface quality.[13] Overall, Material Jetting stands as a pivotal additive manufacturing method, pushing boundaries in precision and complexity. As technology advances, Material Jetting continues to expand its applications, driving innovation across industries and enabling the creation of intricate, high-quality objects with unparalleled detail.
Principle: Prints droplets of liquid photopolymer that solidify layer by layer.
Materials: Photopolymers.
Applications: High-detail models, multi-material prints.

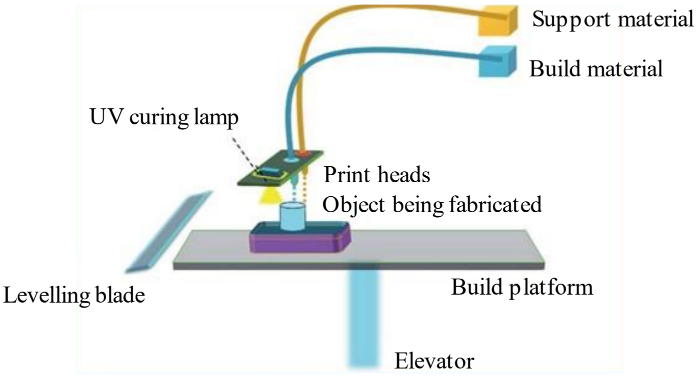

Figure 9. Material jetting [21].

4. *Bio printing Figure. No. 10:* Bio printing is an innovative additive manufacturing process that involves the precise layer-by-layer deposition of biological materials, such as cells, biomaterials, and growth factors, to create three-dimensional living structures. It's a revolutionary technology with immense potential in various fields, including regenerative medicine, tissue engineering, pharmaceuticals, and personalized medicine. In bio printing, specialized printers equipped with multiple print heads are used to deposit bio inks containing living cells onto a substrate according to a digital blueprint of the desired structure. These bio inks can be composed of different types of cells, such as stem cells, differentiated cells, or patient-derived cells, mixed with supportive biomaterials such as hydrogels or scaffolds. The process of bio printing involves precise control over parameters such as cell type, cell density, material composition, and spatial distribution. After deposition, the bio inks undergo various processes such as crosslinking, maturation, and differentiation to promote cell viability, functionality, and tissue formation.[14] Bio printing holds great promise for creating complex tissues and organs that can be used for transplantation, disease modelling, drug testing, and understanding biological processes. It offers the potential to overcome limitations associated with traditional tissue engineering techniques, such as manual cell seeding and scaffold fabrication. However, bio printing is still a rapidly evolving field facing several challenges, including optimizing cell viability and function during and after printing, achieving vascularization within printed tissues, and ensuring the long-term stability and integration of bio printed constructs in vivo. Overall, bio printing represents a transformative technology with the potential to revolutionize healthcare by providing personalized solutions for tissue repair and replacement. Ongoing research and advancements in bio printing techniques, materials, and bio inks are expected to further unlock its capabilities and pave the way for ground-breaking applications in regenerative medicine and beyond.
   Principle: Deposits living cells layer by layer to create biological tissues.
   Materials: Biological inks, cells [7].
   Applications: Medical research, tissue engineering.

5. *Continuous liquid interface production (CLIP) figure. no.11*: Continuous Liquid Interface Production (CLIP) is an innovative additive manufacturing technology developed by Carbon, a leading company in the field of 3D printing. CLIP is a breakthrough in the realm of resin-based 3D printing, offering unprecedented speed, accuracy, and versatility. At its core, CLIP relies on a process known as photochemical curing, which is fundamentally different from traditional layer-by-layer 3D printing methods. In CLIP, a liquid resin is solidified into a solid object continuously, rather than in discrete layers.[5] This is achieved by projecting light through an oxygen-permeable window into a reservoir of liquid resin. The light selectively cures the resin, while oxygen inhibits its polymerization. By carefully controlling the interplay between light and oxygen, CLIP enables the creation of complex shapes with remarkable speed and precision. One of the key advantages of CLIP is its ability to produce parts at speeds up to 100 times faster than traditional 3D printing methods, while still maintaining high resolution and surface quality. This makes CLIP particularly well-suited for rapid prototyping, mass customization, and end-use

production across a wide range of industries, including automotive, aerospace, healthcare, and consumer goods. Furthermore, CLIP offers versatility in materials, allowing for the use of a variety of resins with different properties, including elastomers, rigid plastics, and biocompatible materials. This versatility enables the fabrication of parts with tailored mechanical, optical, and biological properties to suit specific applications.[8] Overall, Continuous Liquid Interface Production represents a significant advancement in additive manufacturing technology, offering unprecedented speed, precision, and material flexibility. As CLIP continues to evolve and mature, it is poised to revolutionize the way we design, prototype, and manufacture a wide range of products, driving innovation and transforming industries across the globe.

Principle: Uses a continuous liquid interface to rapidly cure resin.

Materials: Resin-based photopolymers.

Applications: High-speed printing, functional prototypes.

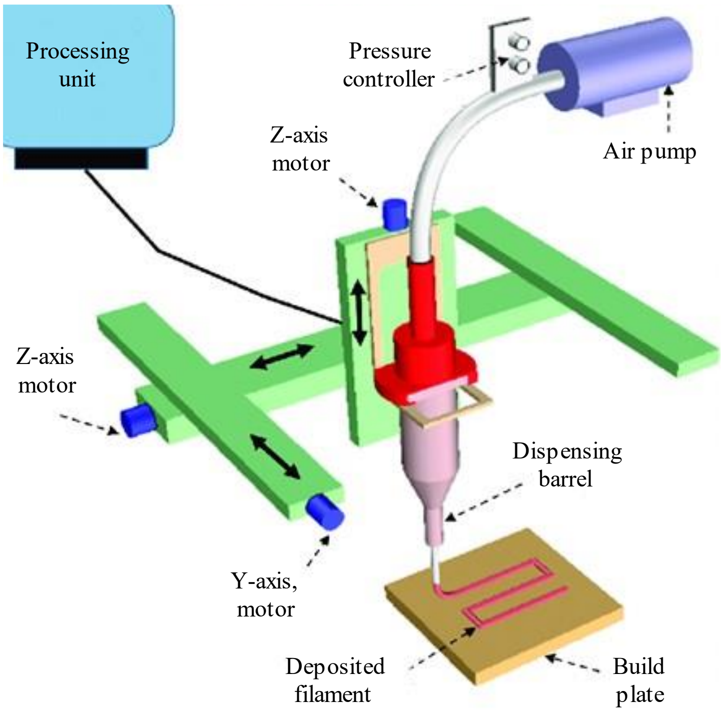

Figure 10. Bio printing [22].

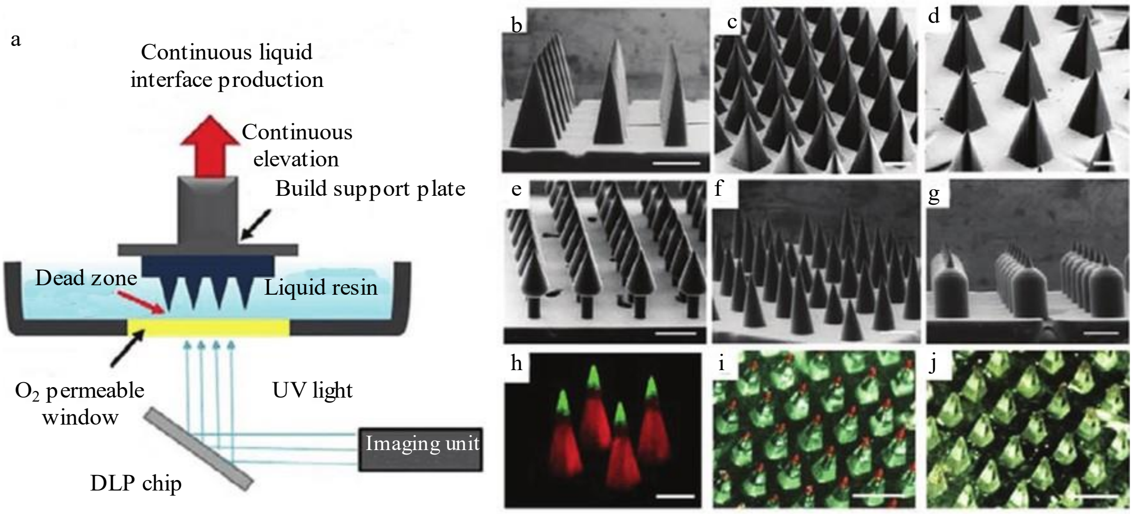

Figure 11. Continuous liquid interface production [23].

APPLICATIONS AND CASE STUDIES

a. *Consumer goods*: Biodegradable filaments are increasingly used for creating consumer products such as packaging materials, disposable cutlery, and household items. The use of 3D biodegradable filaments in consumer goods offers various applications, contributing to sustainable and environmentally friendly product development. Here are several applications in the consumer goods sector:

1. *Eco-friendly packaging*: Eco-friendly packaging utilizing biodegradable filament offers a sustainable solution to the environmental challenges posed by traditional packaging materials. By utilizing bio-based polymers such as PLA or PHA, packaging designers can create versatile and customizable packaging designs that reduce reliance on fossil fuel-based plastics. Biodegradable filament enables the creation of packaging materials that break down naturally over time, minimizing waste accumulation in landfills and ecosystems. This not only aligns with the principles of a circular economy but also enhances brand reputation by appealing to environmentally conscious consumers.[4] Collaboration across the supply chain is crucial to ensure the successful implementation of eco-friendly packaging solutions using biodegradable filament.
2. *Customized consumer products*: Customized consumer products made with biodegradable filament offer a sustainable alternative to traditional manufacturing methods, catering to the growing demand for eco-friendly options. Biodegradable filaments, derived from renewable resources such as PLA or PHA, enable the creation of personalized products that align with environmental values. Whether it's custom-designed phone cases, household items, or fashion accessories, biodegradable filament allows for flexibility in design and functionality while minimizing the environmental footprint. By harnessing additive manufacturing technologies like 3D printing, manufacturers can produce tailored products on-demand, reducing waste and energy consumption associated with mass production and transportation. This shift towards customized consumer products not only promotes sustainability but also fosters a deeper connection between consumers and the products they use, reinforcing the importance of conscious consumption in a rapidly evolving market landscape [6].
3. *Biodegradable utensils and tableware*: Biodegradable utensils and flatware created from bio-degradable fibre show an economical arrangement to the natural challenges postured by customary plastic utensils. Utilizing materials such as PLA or PHA, these biodegradable fibres offer a renewable and eco-friendly elective, determined from normal assets like corn starch or sugarcane. Biodegradable utensils and silverware can be customized to meet different needs, giving flexibility in plan, shape, and usefulness. From expendable cutlery and plates for occasions to tough reusable utensils for every day utilize, biodegradable fibre permits for the creation of a wide extend of items that are both down to earth and naturally capable.[4] By picking for biodegradable utensils and silverware, shoppers can decrease their dependence on single-use plastics, minimize squander era, and contribute to the conservation of environments. This move towards economical choices underscores the significance of cognizant utilization and economical hones in forming a greener future for eras to come.
4. *Children's toys:* Creating children's toys with biodegradable filament offers a sustainable and safe alternative to traditional plastic toys. Utilizing bio-based materials like PLA or PHA, these biodegradable filaments provide a renewable and eco-friendly option for toy manufacturing. Whether its building blocks, figurines, or puzzles, biodegradable filament allows for the production of colourful and durable toys that are free from harmful chemicals often found in conventional plastics. These toys are not only safe for children to play with but also contribute to reducing plastic pollution and protecting the environment. By choosing biodegradable toys, parents can instil eco-conscious values in their children from an early age, fostering a sense of responsibility towards the planet. Moreover, the versatility of biodegradable filament enables the creation of custom-designed toys, sparking creativity and imagination in young minds while promoting sustainability for future generations [7].

5. *Biodegradable gardening products*: Biodegradable gardening products crafted from biodegradable filament offer a green solution for gardening needs while being gentle on the environment. These products, made from materials like PLA or PHA, provide a renewable option compared to traditional plastic tools and accessories. They include items such as plant pots, seedling trays, garden markers, and compost bins, all designed to naturally break down over time without leaving harmful residues in the soil [3]. Choosing biodegradable gardening products supports eco-friendly gardening practices, promotes healthier plant growth, and reduces plastic waste for a greener planet.
6. *Travel accessories*: Crafting travel accessories with biodegradable filament presents a sustainable approach to traveling while minimizing environmental impact. By utilizing materials such as PLA or PHA, these biodegradable filaments offer a renewable alternative to traditional plastic travel accessories [24]. From luggage tags and passport holders to toiletry containers and travel organizers, biodegradable filament enables the production of a variety of travel essentials that are both practical and eco-friendly [9] These accessories are designed to naturally break down over time, reducing plastic waste and contributing to a cleaner environment. Choosing biodegradable travel accessories supports sustainable travel practices and helps to protect natural ecosystems, making every journey a greener one.

b. *Medical printing*: The medical field has explored the use of biodegradable filaments for printing implants, prosthetics, and drug delivery systems, capitalizing on the materials' biocompatibility.

1. *Biodegradable materials in medicine*: Discuss the types of biodegradable materials commonly used in 3D printing for medical purposes, such as bio inks, polylactic acid (PLA), polyglycolic acid (PGA), and other biocompatible polymers. Highlight the importance of these materials in promoting tissue regeneration and reducing the environmental impact.
2. *Customized medical implants*: Explore the application of 3D biodegradable printing in creating customized implants for orthopaedic and dental surgeries. Discuss how personalized implants improve patient outcomes, accelerate recovery, and reduce the risk of rejection compared to traditional implants.
3. *Drug delivery systems*: Examine the role of 3D biodegradable printing in designing intricate drug delivery systems. Discuss the potential for personalized medicine and the controlled release of pharmaceuticals using biodegradable materials, enhancing treatment efficacy while minimizing side effects [3].
4. *Tissue engineering and regeneration*: Explore how 3D biodegradable printing contributes to tissue engineering and regeneration. Discuss the creation of scaffolds and structures that mimic the natural environment, promoting cell growth and tissue regeneration in applications such as skin grafts, cartilage repair, and organ transplantation.
5. *Sustainable medical prototyping*: Discuss the environmental benefits of using biodegradable materials in medical prototyping. Explore how 3D biodegradable printing reduces waste, energy consumption, and the ecological footprint associated with traditional prototyping methods.

c. *Educational initiatives*: Educational institutions are incorporating biodegradable filaments into 3D printing curricula, fostering sustainability awareness among future generations of designers and engineers.

1. *Empowering STEM education*: Layer by layer, three-dimensional items are created using stereolithography (SLA), an additive manufacturing technique that employs a liquid resin that is cured by ultraviolet (UV) radiation.From creating geometric shapes to complex prototypes, students gain practical insights into the principles of design and engineering.
2. *Sustainable design and prototyping*: Explore how educational institutions are incorporating 3D biodegradable printing to teach sustainable design principles. Students can prototype eco-friendly products and explore the environmental impact of materials, fostering a sense of responsibility toward sustainable practices.
3. *Biodegradable printing in art and design programs*: Examine the integration of 3D biodegradable printing in art and design courses. Discuss how students can unleash their creativity by experimenting with sustainable materials, pushing the boundaries of traditional artistic expression [4].

4. *Cross-disciplinary learning*: Highlight how 3D biodegradable printing serves as a catalyst for cross-disciplinary collaboration. Students from various disciplines can work together on projects that integrate science, engineering, art, and environmental studies, promoting a holistic approach to problem-solving.
5. *Community engagement and outreach*: Discuss how educational institutions are leveraging 3D biodegradable printing to engage with local communities. Initiatives such as creating biodegradable products for community use or addressing local environmental challenges empower students to make a positive impact [7].
6. *Encouraging innovation and entrepreneurship*: Explore how 3D biodegradable printing fosters innovation and entrepreneurship among students. Students can bring their ideas to life, prototype sustainable solutions, and even develop small-scale businesses centred on eco-friendly products.

Materials That Are Not Used for Bio Printing

Several materials are not suitable for 3D printing due to their physical properties, safety concerns, or the limitations of current 3D printing technologies. Here are some examples:

1. *Rubber*: Traditional rubber is too flexible and soft to be extruded through the nozzles of most 3D printers. Specialized flexible filaments like TPU (Thermoplastic Polyurethane) are available as alternatives.
2. *Glass*: While there are experimental techniques for 3D printing glass, it is generally not suitable for typical consumer 3D printers due to its high melting point and brittleness.
3. *Wood*: Pure wood cannot be used in standard 3D printers. However, wood-filled PLA filaments that contain wood fibres mixed with PLA are available and can mimic wood-like finishes.
4. *Metals*: Most consumer 3D printers cannot handle pure metals due to the high temperatures required for melting. Metal 3D printing is possible with specialized industrial printers using processes like SLM (Selective Laser Melting) or DMLS (Direct Metal Laser Sintering).
5. *Ceramics*: While ceramic 3D printing exists, it is complex and requires special equipment to sinter and finish the material, making it unsuitable for most standard 3D printers.
6. *Certain plastics*: PVC (Polyvinyl Chloride): Releases harmful fumes when melted, making it unsafe for 3D printing.- Polystyrene: While it can technically be printed, it is brittle and difficult to work with.
7. *Paper*: Paper cannot be extruded in a standard 3D printer. However, there are specialized 3D printing technologies that can layer paper sheets to create objects.

These materials require specialized equipment or are incompatible with the extrusion-based 3D printing methods most commonly used.

TENSILE STRENGTHS OF BIO DEGRADABLE MATERIALS

Tensile strength values are typically reported in megapascals (MPa) or pounds per square inch (psi). These values can vary depending on factors such as filament quality, printing parameters, and testing methods. The provided ranges give a general idea of the tensile strengths of each material.

ENVIRONMENTAL IMPLICATIONS AND CHALLENGES

Environmental implications and challenges encompass a multitude of interconnected issues that profoundly impact the health of our planet and the well-being of its inhabitants. Climate change stands out as a paramount concern, driven by the relentless emission of greenhouse gases from human activities, leading to a cascade of effects such as rising temperatures, extreme weather events, and habitat disruption. Biodiversity loss follows closely behind, accelerated by habitat destruction, pollution, and invasive species, threatening the stability of ecosystems and the services they provide [4]. Pollution, whether in the form of air, water, or soil contamination, poses significant risks to both environmental and human health, stemming from industrial processes, agriculture, and inadequate waste management. Deforestation compounds these challenges, diminishing biodiversity, exacerbating climate change, and undermining the vital role forests play in carbon sequestration and ecosystem regulation. Resource depletion further strains the environment, driven by unsustainable consumption patterns and inefficient resource use, while water scarcity intensifies as populations grow, industries expand, and climate variability disrupts hydrological cycles. The degradation of oceans, marked by overfishing, pollution, and acidification, threatens marine ecosystems and the livelihoods of coastal communities. Waste management emerges as another critical issue, with mounting volumes of waste contaminating land, waterways, and the atmosphere, necessitating improved disposal methods and reduced reliance on single-use materials. Addressing these challenges demands collaborative action at all levels, encompassing policy reforms, technological innovations, sustainable resource management practices, and public engagement to foster a more resilient and equitable future for all [9].

Table 2. Tensile strength of several biodegradable materials.

Material	Ultimate Tensile Strength (MPa)	Elongation (%)	Young modulus (MPa)
ABS	19.7-29.2	1.5-8.9	1910-2050
PC	29.5-36.9	3-6.7	1620-2000
PLA	49.6-65.7	1.7-5.0	2800-3600
PLA recycled once	51	1.88	3093±194
PLA recycled 5 times	48.8	1.68	3491±98
PLA/PHA + 10–20% fiber	20-30	0.9-1.1	3500-4000
PLA/PHA + 10–20% fiber water saturated	15-20	0.5-0.8	3100-3600
PLA + 5% pine lignin	40.4-43.6	2.31-2.85	2160-2200
TPS/ABS biomass	34.8-46.8	NA	NA
PLA + graphite 2%	50	8.1	NA
PLA + graphite 8%	62	6.1	NA
HDPE virgin	25.5	16.2	463.4
HDPE recycled once	25.5	25.5	428.4

Degradation in Different Environments

Degradation in different environments encompasses a spectrum of challenges that compromise the health and integrity of ecosystems worldwide. In terrestrial ecosystems, deforestation stands out as a primary form of degradation, driven by agricultural expansion, logging, and urbanization. Loss of forest cover not only diminishes biodiversity but also disrupts carbon sequestration, exacerbating climate change. Soil degradation, resulting from erosion, salinization, and depletion of nutrients due to unsustainable agricultural practices, further undermines ecosystem productivity and resilience. In aquatic environments, pollution poses a significant threat, with industrial effluents, agricultural runoff, and plastic waste contaminating rivers, lakes, and oceans. Water pollution not only harms aquatic life but also jeopardizes human health, affecting drinking water sources and food supplies. Overfishing and destructive fishing practices contribute to the degradation of marine ecosystems, leading to declines in fish stocks, habitat destruction, and loss of biodiversity. With the use of a liquid resin that has been UV-cured, stereolithography (SLA) is an additive manufacturing technique that builds three-dimensional things layer by layer.Urban environments face unique degradation challenges, including air pollution from vehicle emissions, industrial activities, and construction dust. Poor waste management practices in cities result in the accumulation of solid waste in landfills, leading to pollution of soil and groundwater.[8] Urban sprawl encroaches upon natural habitats, fragmenting ecosystems and reducing green spaces essential for biodiversity and human well-being. Moreover, the heat island effect exacerbates urban temperatures, contributing to heat-related health issues and increasing energy consumption for cooling. Mountainous regions experience degradation due to factors such as deforestation, soil erosion, and glacial retreat, exacerbated by climate change. Loss of forest cover in mountainous areas leads to heightened landslide risks, soil erosion, and diminished water quality downstream. Glacial meltwater, crucial for freshwater resources and ecosystem stability, is diminishing rapidly, affecting downstream communities dependent on these resources. Addressing degradation in diverse environments requires holistic approaches that prioritize conservation, sustainable resource management, and climate resilience. Efforts to protect and restore ecosystems must be coupled with measures to mitigate and adapt to climate change, promote sustainable land-use practices, and foster community engagement in environmental stewardship.[10] By recognizing the interconnectedness of environmental degradation across different landscapes and adopting integrated solutions, we can work towards a more sustainable and equitable future for all.

FUTURE DIRECTIONS AND OPPORTUNITIES

The future of biodegradable filament holds immense promise as society increasingly seeks sustainable alternatives to conventional plastics in various industries, particularly in 3D printing. Here are some potential directions and opportunities for biodegradable filament:

1. *Material innovation*: Continued research and development into novel biodegradable materials offer opportunities to expand the range of options available for biodegradable filaments. Using a liquid resin that has been cured by ultraviolet (UV) light, stereolithography (SLA) is an additive manufacturing technique that builds three-dimensional things layer by layer. Further advancements in material science could lead to filaments with enhanced strength, durability, and compatibility with different printing techniques.
2. *Functional additives*: Incorporating functional additives into biodegradable filaments can enhance their performance and versatility. Additives such as reinforcing fibres, antimicrobial agents, flame retardants, and UV stabilizers can improve the mechanical properties, durability, and resistance to environmental factors of biodegradable prints, expanding their potential applications across industries.
3. *Customization and tailoring:* With advancements in 3D printing technology, there's an opportunity to tailor biodegradable filament properties to specific applications. Customization of filament characteristics, such as flexibility, rigidity, colour, and degradation rate, can meet the diverse needs of different industries, from medical devices and packaging to consumer products and construction materials.
4. *Circular economy initiatives*: Integrating biodegradable filament into circular economy initiatives offers opportunities to close the loop on plastic waste. By designing products for disassembly, recycling, or composting at the end of their life cycle, biodegradable prints can contribute to reducing waste and minimizing environmental impact. Collaboration among stakeholders along the value chain, including manufacturers, recyclers, policymakers, and consumers, is essential to optimize resource recovery and promote a circular economy for biodegradable materials.
5. *Education and awareness:* Increasing awareness and educating stakeholders about the benefits and proper use of biodegradable filament can drive demand and adoption. Outreach efforts targeting designers, engineers, manufacturers, and consumers can promote sustainable design practices, encourage the use of biodegradable materials, and foster responsible end-of-life management of 3D printed products.
6. *Regulatory support and standards*: Establishing clear regulatory frameworks and standards for biodegradable filament can provide guidance to manufacturers, ensure product quality and safety, and facilitate market access. Regulatory support, incentives, and certification schemes that promote the use of biodegradable materials can incentivize innovation and investment in sustainable 3D printing solutions.
7. *Collaborative research and partnerships*: Collaborative research initiatives and partnerships between academia, industry, and government can accelerate innovation and address technical challenges in biodegradable filament development. By pooling resources, expertise, and infrastructure, stakeholders can advance the state-of-the-art in biodegradable materials, scale up production, and bring sustainable 3D printing solutions to market more efficiently. In summary, the future of biodegradable filament holds great potential for driving sustainability in 3D printing and beyond. By fostering innovation, collaboration, and responsible consumption, biodegradable filament can play a pivotal role in reducing plastic pollution, conserving resources, and promoting a more sustainable future for generations to come.

CONCLUSION

In conclusion, the emergence of biodegradable filament signifies a pivotal stride in the quest for sustainable materials, particularly within the realm of 3D printing and beyond. With escalating concerns over plastic pollution and environmental degradation, the development and utilization of biodegradable filament offer a beacon of hope, promising to mitigate the adverse impacts associated with traditional plastics while paving the way for a more environmentally conscious future. Looking forward, the trajectory of biodegradable filament appears exceedingly promising, buoyed by a confluence of factors spanning technological innovation, circular economy principles, and collaborative endeavours. Advancements in material science continue to unlock new frontiers, expanding the repertoire of bio-based polymers and enhancing the mechanical properties and applicability of biodegradable filaments across diverse industries and applications. Moreover, the integration of functional additives holds vast potential to augment the performance and versatility of biodegradable filaments, enabling tailored solutions that cater to specific needs and requirements. Whether reinforcing fibers to bolster structural integrity, incorporating antimicrobial agents for hygiene-sensitive applications, or imbuing UV stabilizers for outdoor durability, these additives further amplify the value proposition of biodegradable materials. Crucially, the paradigm of circular economy underpins the sustainable utilization of biodegradable filament, advocating for a holistic approach that extends beyond mere production and consumption to encompass the entire lifecycle of materials. By designing products with end-of-life considerations in mind, embracing principles of disassembly, recycling, and composting, biodegradable filament can catalyse a transition towards closed-loop systems that minimize waste, conserve resources, and mitigate environmental impact. The research discusses the utilization of plant biomass in creating bio composite materials for 3D printing. It highlights the benefits of using renewable resources in developing sustainable printing materials.[25] Furthermore, the imperative of education and awareness looms large, underscoring the need to disseminate knowledge and foster a culture of sustainability among stakeholders. Through outreach initiatives targeting designers, manufacturers, policymakers, and consumers alike, we can in still a collective ethos of responsibility and stewardship, driving demand for biodegradable materials and engendering widespread adoption across industries. The study identified optimal settings for focal distance and cutting speed that improve the cutting geometry, specifically for mean kerf width, down width, upper width, and surface roughness of ASA thin plates [26]. In concert with regulatory support, standards development, and collaborative research endeavours, the future of biodegradable filament stands poised for transformative impact. By harnessing the collective ingenuity, resources, and resolve of global stakeholders, we can harness the potential of biodegradable filament to chart a course towards a more sustainable, equitable, and resilient future for generations to come. Various other compatible materials like Semi-interpenetrating networks (semi-IPNs), Interpenetrating networks (IPNs) and cross-linked binary graft copolymers (BGCPs) have used [27].

REFERENCES

1. Gibson I, Rosen DW, Stucker B. Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing. Springer; 2014.
2. Hull CW. Apparatus for production of three-dimensional objects by stereolithography. U.S. Patent No. 4,575,330. 1986.
3. Ojeda T, Rodriguez JF. A comprehensive review on the properties and applications of 3D printing materials. Materials Today Communications. 2021;26:102086.
4. Pérez-Pardo MA, Medina-Sánchez G. Recent progress and future prospects in 3D printing of thermosetting polymers. Polymers. 2018;10(12):1327.
5. Huang W, Leu MC, Mazumder J. A review of 3D printing materials and methods for soft robotics. Rapid Prototyping Journal. 2015;21(2):186-194.
6. Kruth JP, Leu MC, Nakagawa T. Progress in additive manufacturing and rapid prototyping. CIRP Annals. 1998;47(2):525-540.
7. Chia HN, Wu BM. Recent advances in 3D printing of biomaterials. Journal of Biological Engineering. 2015;9(1):4.

8. Tran NH, Rahman SA. A review on the development of natural fibre bio-composites for structural applications. Journal of Reinf. Plastics and Composites. 2018;37(24):1435-1449.
9. Singh S, Bajpai J. Development and characterization of PLA-based biocomposites reinforced with natural fibers: A review. Journal of Polymers and the Environment. 2018;26(5):1761-1786.
10. Zhang C, An G. Biodegradable polymers and green-based polymer composites: Present status and future prospects. Materials Today Sustainability. 2021;11-12:100095.
11. Kaisarunnisa S, Gupta A. A review on bio-based filament materials for 3D printing. Materials Today Chemistry. 2021;22:100563.
12. Williams CB, Adewunmi AA. The application of biodegradable polymers in tissue engineering: A review. Journal of Bioactive and Compatible Polymers. 2017;32(6):637-669.
13. Arifin MA, Dimaano M. A review on the utilization of biodegradable materials for 3D printing. Journal of Material Cycles and Waste Management. 2019;21(4):878-895.
14. Iqbal S, Thomas S. Biodegradable polymers and their layered silicate nanocomposites: In greener environments. Polymers. 2020;12(1):199.
15. Singh R, Thakur VK. Biodegradable polymers and green composites for packaging: A review. Environmental Chemistry Letters. 2021;19(4):2633-2647.
16. 16.Balla E, Daniilidis V, Karlioti G, Kalamas T, Stefanidou M, Bikiaris N, Vlachopoulos A, Koumentakou I, Bikiaris D. Poly(lactic Acid): A Versatile Biobased Polymer for the Future with Multifunctional Properties—From Monomer Synthesis, Polymerization Techniques and Molecular Weight Increase to PLA Applications. Polymers. 2021;13:1822.
17. 17.Reddy V, Ramanaiah SV, Reddy M, Chang YC. Review of the Developments of Bacterial Medium-Chain-Length Polyhydroxyalkanoates (mcl-PHAs). Bioengineering. 2022;9:225.
18. 18.Surendren A, Mohanty AK, Liu Q, Misra M. A review of biodegradable thermoplastic starches, their blends and composites: recent developments and opportunities for single-use plastic packaging alternatives. Green Chemistry. 2022;24(22):8606-8636.
19. 19.Aliotta L, Seggiani M, Lazzeri A, Gigante V, Cinelli P. A Brief Review of Poly (Butylene Succinate) (PBS) and Its Main Copolymers: Synthesis, Blends, Composites, Biodegradability, and Applications. *Polymers*. 2022;14:844.
20. 20.Zhang, Q., Song, M., Xu, Y., Wang, W., Wang, Z., & Zhang, L. (2021). Bio-based polyesters: Recent progress and future prospects. *Progress in Polymer Science*, 120, 101430.
21. 21.Gülcan, O., Günaydın, K., & Tamer, A. (2021). The State of the Art of Material Jetting—A Critical Review. *Polymers*, 13, 2829.
22. 22.Habib, A., Ahasan, & Sathish, V., Mallik, S., & Khoda, B. (2018). 3D Printability of Alginate-Carboxymethyl Cellulose Hydrogel. *Materials*, 11, 454.
23. 23.Johnson, A., Caudill, C., Tumbleston, J., Bloomquist, C., Moga, K., Ermoshkin, A., Shirvanyants, D., Mecham, S., Luft, J., & DeSimone, J. (2016). Single-Step Fabrication of Computationally Designed Microneedles by Continuous Liquid Interface Production. *PLOS ONE*, 11.
24. 24. Gupta A. Preparation of ethyleneamine functionalized crosslinked poly (acrylonitrile-ethylene glycoldimethacrylate) chelating resins for adsorption of lead ions, Separation of Science & Tchnology, 52(3), 447-445, 2016.
25. 25. Andanje MN, Mwangi JW, Mose BR, Carrara S. Biocompatible and biodegradable 3D printing from bioplastics: A review. Polymers.
26. 26. Kechagias, J.D., Ninikas, K., Vakouftsi, F. *et al.* Optimization of laser beam parameters during processing of ASA 3D-printed plates. *Int J Adv Manuf Technol* 130, 527–539 (2024). https://doi.org/10.1007/s00170-023-12711-4
27. 27. P Mehta, M Sharma, M Devi -Hydrogels: An overview of its classifications, properties, and applications, Journal of the Mechanical Behavior of Biomedical, 2023. 10.1016/j.jmbbm.2023.106145. Epub 2023 Sep 28.