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Industrial *Cannabis sativa* (Fiber or Hemp): 3D printing-hempcrete-a sustainable building material

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Abstract

Industrial Cannabis sativa (hemp or fibre) is mainly used to produce paper, ropes, food, medicines, cosmetics, hempcrete, leather, bioplastic, biochar, 3D printing homes and textiles. Hempcrete is a building construction material made from Industrial hemp fibers, lime and water. Hempcrete is a cost effective and sustainable properties which makes as a promising material in both new projects and those involving renovation. 3D printing, also known as additive manufacturing, is a method of creating a three dimensional object layer-by-layer using a computer created design. The process works by laying down thin layers of material in the form of liquid or powdered plastic, metal or cement, and then fusing the layers together. Hemp has been applied in filaments for 3D printing. Hemp filament is a promising and sustainable alternative to traditional 3D printing materials. The 3D printing industry has been integrating hemp into its technology. Hemp can be transformed into filament to be used for 3D printing. 3D printing is used to apply computer-aided design (CAD) files of 3D objects, which are digitally designed for use in different applications or obtained by scanning an existing object through therapeutic prototyping or rapid manufacturing. The building construction with 3D printing technologies could be a game-changer and Tvasta Manufacturing Solutions, Chennai, with IIT Madras, Tamil Nadu, India has constructed the first 3D printed buildings in India. The efficiency of 3D printing outpaces traditional building times and methods. As the world of 3D printing continues to evolve, hemp filament is emerging as a viable and eco-friendly alternative. Hemp filament shares many printing properties with polylactic acid (PLA), making it easy to use for various 3D printing applications. One of the biotechnology company, Makeinica at Bengaluru, Karnataka, India has developed manufacturing process, and practical applications of hemp filament in 3D printing, with a focus on its potential for 3D printing services in India. Several companies have developed their versions of hemp 3D printer filament, contributing to the growing market for biodegradable and sustainable materials.

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1. Introduction

Cannabis sativa L. belongs to the family *Cannabaceae* was used as a medicine before the Christian era in Asia**,** mainly in India**,** China, Bhutan, Nepal, Afghanistan, Pakistan, Egypt, Africa, Iran, Persians and Latin America [1-43]. According to ***Ayuverda*** in India, the medicinal value of the *Cannabis sativa* plants was well documented as **Vijaya** and often known **as** Desi Vijaya [1-40]. This was the first Indian written evidence to support the medicinal value of *Cannabis sativa* plants which was well documented in *Ayuverda* in India[1-42]. *Cannabis sativa* has a long history in India, recorded in legends and religion [1-40]. It was found in various habitats ranging from sea level to the temperate and alpine foothills of the Indian Himalaya Region from where it was probably spread over the last 10,000 years [1-42]. Many historians believed that Indian Himalayan Region was the centre of origin of *Cannabis sativa* L. and *Cannabis indica* [1-42]. The use of *Cannabis sativa* as a herbal medicine is increasing due to its proven therapeutic values. However, in multiple countries today, its cultivation and usage are regulated by the interest in the medicinal potential of cannabis and have paved the way for the release of marketing authorization for cannabis-based products. The legalization of cannabis is an important source of economic growth as it contributes to the growing revenue tax, and the creation of new workplaces.

Cannabis sativa L. is a wind-pollinated, dioecious medicinal plant (i.e., the male and female reproductive structures are on separate plants), although monoecious plants (male and female flowers on same plant) can occur in some population [1-40]. Male plants die shortly after flowering [1-42]. The female plants live 3 to 5 weeks until seed is fully riped [1-40]. Therefore, the plants are obligatory out-crossers[1-40]. In commercial production, Medical *Cannabis sativa* (drug or marijuana type) plants are all genetically female and male plants are destroyed as seed formation reduces flower quality [1-40]. Monoecious individuals are found with hermaphrodite flower or bisexual inflorescence [1-42].

Cannabis sativa L., is classified into two types as Medical *Cannabis sativa* L.(drug or marijuana), and Industrial *Cannabis sativa*, (fiber or hemp) based on its Λ9-tetrahydrocannabinol (THC) content [1-43]. Medical *Cannabis sativa* (drug or marijuana) contains very high levels of THC (above 0.3 to 38% of dry weight) and grown inside the greenhouse controlled conditions for the production of unfertilized female flowers [1-41]. Medical *Cannabis sativa* (drug or marijuana) is also known as ganja, charas and bhang which is not yet legalized, prohibited and banned in India due to the presence of high levels of psychoactive narcotic substance, THC (above 0.3 to 38% of dry weight). This is used only for the medical and research purposes under special permission from the Government of India. The use, sale, growth of Medical *Cannabis sativa* L. (drug or marijuana) in India is still illegal and needs special permission or license from the Government of India [1- 41].

Industrial *Cannabis sativa*, (fiber or hemp) is used as a functional food and medicine since it contains Cannabidol (CBD), and very low levels of THC [1-40]. Therefore, Industrial *Cannabis sativa* L. (fiber or Hemp) is genetically modified variety with very low levels of Λ9-tetrahydrocannabinol (THC) (0 to 0.3 %)[1-40]. Industrial *Cannabis sativa*, (fiber or hemp) and Medical *Cannabis sativa* L.(drug or marijuana) share the same species, *Cannabis sativa* L, but represent different varieties [1-41]. As such, there are genetic differences that lead to different chemical characteristics, which, in turn, lead to different uses [41-51].

On the other hand Industrial *Cannabis sativa* L. (Hemp) contains very low levels of Λ9-tetrahydrocannabinol (THC) (0 to 0.3% of dry weight) grown outside in a large agriculture farms for the production of fiber, seeds and oil [1-41]. Industrial *Cannabis sativa* L. (fiber or Hemp) is legalized by FOOD SAFETY AND STANDARDS AUTHORITY OF INDIA (FSSAI), Government of India, New Delhi since 2021 grown for seed, fiber, medicine, as the functional food, fiber and hempcrete in Uttarakhand state, India. In 2021, Uttarakhand state, India became the first Indian state to permit large-scale commercial cultivation of industrial hemp [1-41]. The license was awarded to the Indian Industrial Hemp Association (IIHA) to plant cannabis on 1,000 hectares. In 2025, another Indian state, Himachal Pradesh has been legalized for the growth of hemp as pilot plant project [1- 41].

Therefore, Industrial hemp differs from marijuana in the level of Λ9-tetrahydrocannabinol (THC) present in the plant [1-41]. Λ9-tetrahydrocannabinol (THC) is the chemical most responsible for the psychoactive properties in the Medical *Cannabis sativa* L.(drug or marijuana) [1- 41]. Industrial *Cannabis sativa* L. (fiber or hemp) has traditionally been defined as having less than 0.3 percent THC, although in some U.S. states it is now defined as having no more than 0.5 % percent THC [1- 41]. They have also established a maximum standard of 10 parts per million (ppm) for THC residue in hemp products, including grain, flour, and oil (Agriculture and Agri-Food Canada, 2013) [1-41]. However, due to the presence of psychoactive molecules, Λ9-tetrahydrocannabinol (Λ9-THC) and Λ8-tetrahydrocannabinol (Λ8-THC), cannabis cultivation and its use is restricted/regulated in many countries [1-41]. Industrial hemp (fiber type) is a multi-purpose crop. The unique properties of the plant make it a highly valuable and sustainable crop[1- 41].

Industrial *Cannabis sativa* (hemp or fiber) is mainly used to produce paper, ropes, food, medicines, cosmetics, hempcrete, leather, bioplastic, biochar, 3D printing homes [1-44-77] and textiles [1-40]. This wide range of applications makes hemp a unique plant that can have positive impacts in many industries [1-40, 41-51]. Hemp fibers are used in paper, carpeting, home furnishing, construction materials, insulation materials, auto parts, composites, insulation materials and bio-composites consume a significant. Hemp seed delivers a desirable ratio of Omega-6 to Omega-3 PUFA, which can improve cardiovascular health, reduce osteoporosis symptoms, and diminish eczema conditions [1-40, 41-51]. Cannabidiol (CBD) exerts pharmacological properties that make it a potential therapeutic agent for central nervous system diseases, such as epilepsy, neurodegenerative diseases, and multiple sclerosis [1-40, 41-51]. The hemp seeds and sprouts to be rich in beneficial bioactive compounds with both in vitro and ex vivo antioxidant activities [1-40, 41-51]. Hemp fiber meal can be used for isolation of essential amino acids, especially Arginine, by using food grade enzymes for polysaccharide digestion[1-40, 41-51].

Cellulosic fibers such as hemp, flax, jute, sisal, coir, bamboo, banana, kenaf, and ramie are used as reinforcement in natural fiber-reinforced polymer composites (NFRPCs) and are abundant in many countries. Lignocellulosic fibers such as jute, sisal, flax, and hemp have been reported to be an alternative to glass-fiber and carbon-fiber-reinforced composites in various applications [44-77]. Hempcrete is a plant based sustainable building construction material that is made with a low environmental impact that removes waste production, decreases both energy use and the consumption of natural resources [1-8, 78-126]. Hempcrete is a building construction material made from Industrial hemp fibres, lime and water [1-8, 78-126]. 3D printing is used to apply computer-aided design (CAD) files of 3D objects, which are digitally designed for use in different applications or obtained by scanning an existing object through therapeutic prototyping or rapid manufacturing [44-77]. Recently the thermal, chemical, mechanical, and morphological properties of an alkali-treated hemp fiber-reinforced PC composite that can be formed with a 3D printer for architectural applications has been reported [44-77]. Three-dimensional (3D) printing is an additive manufacturing process that creates a physical object from a digital design [44-77]. The process works by laying down thin layers of material in the form of liquid or powdered plastic, metal or cement, and then fusing the layers together [44-77]. Hemp has been applied in filaments for 3D printing, as a harmonic steel cable net replacement, as fiber reinforcement for automotive composite parts, and for the production of carbon nanosheets as a replacement for graphene in supercapacitors [44-77].

After the legalization of Industrial *Cannabis sativa* (hemp or fiber type) in 2021 in India, there are many efforts and hemp research work is slowly gaining interest and training programmes about hemp production, organic farming, promoting marketing hemp products are successful. Some of the Indian biotech companies are a Bangalore, Karnataka based Namrata HempCo Limited (NHempCo) was founded by Harshavardhan Reddy Sirupa and Narmrata Reddy Sirupa, Cannasis Wellness, Rajamahendravaram, Andhra Pradesh (Keran Vankayala), Pan India Medical Cannabis and Hemp Association (PIMCHA), Mumbai, Maharashtra state, UKHI-Hemp Foundation, Bombay Hemp Company, BOHECO, Satliva, Himalayan Hemp, Hemp Fabric Lab, Vedi Herbals, Happy Hemp, SUI, ItsHemp, Bhu:Sattva's, Health Horizons, Hemis, Hemp Republic, Hempsters, B.E. Hemp, India Hemp Co., Inc, India Hemp Organics, Health Horizons, Hemis, TheTrost, and Gin-Gin) involved in promoting the Indian hemp products marketing, research, cultivation, harvesting, processing, manufacturing, trading, wholesaling, retailing, innovating, advocating both across the nation and around the world. In the following section, the hemp based building material, hempcrete, and 3D printed hempcrete has been updated and discussed.

2. Industrial *Cannabis sativa* (fiber or hemp): Hempcrete

Hempcrete is a plant based sustainable building construction material that is made with a low environmental impact that removes waste production, decreases both energy use and the consumption of natural resources [1-9, 78-126]. Hempcrete is a building construction material made from Industrial hemp fibers, lime and water [1-9, 78-126]. Hempcrete is a cost effective and sustainable properties which makes as a promising material in both new projects and those involving renovation [1-9, 78-126]. This composite breathes, as well as having good thermal and acoustic-insulation properties [8, 78-126]. For building purposes, the hemp crop's inner woody core, hurds is mixed with a lime-based binder forming a bio-aggregate concrete, known as "Hempcrete" [8, 78-126]. The hemp-lime composite material is mainly used to make walls, although floor slabs, ceiling, and roof insulation can be made [1-9, 78-126]. The relatively denser hempcrete mixture is poured above a base layer into the floor to make floor slabs [8, 78-126]. Hempcrete is a bio-composite mixture of hemp shive, lime binder and water [8, 78-126]. A lightweight material, which is about one eighth the weight of concrete [8, 78-126]. Furthermore, civil engineers confirmed that hempcrete blocks can also be used for roofs as well as the more conventional wall applications since their implementation is easier than other types

[1-9, 78-126]. Archaeologists have confirmed the use of hemp fiber (also called 'shive') in the construction of a bridge, dated to the 6th century AD, in southern France [8, 78-126]. The first modern use of hemp fiber composite construction was in France in 1990 for the renovation of historic timber-framed buildings, casting the hemp lime mixture around the timber frame [8, 78-126]. These buildings are clear proof of the durability of materials based on lime [8, 78-126]. Cement plaster found to be unsuitable as it did not breathe, stopping the escape of moisture and promoting rot; and was not flexible, resulting in surface cracking [8, 78-126]. The hemp and lime product proved to be a natural alternative to cement based concrete [9, 78-126]. Most importantly, hemprete showed a negative carbon footprint making it a suitable material in the construction industry [8, 78-126].

Hempcrete is a building construction material made from hemp fibres, lime and water. Hemprete showed a negative carbon footprint making it a suitable material in the construction industry [8, 78-126]. This composite, hempcrete breathes, as well as having a good thermal and acoustic-insulation properties [8, 78-126]. The use and performance of hempcrete suggested that hempcrete can be considered as an environmentally friendly material [8, 78-126]. In a first of its kind in India, an architect couple, Namrata Kandwal and Gaurav Dixit have built a house made of using hemp fibre-hempcrete in Uttarakhand state, India. Industrial Hemp (fiber-type) is both an agricultural and industrial commodity and stem supplies both cellulosic and woody fibers [8, 78-126]. Hempcrete is a highly breathable material, which allows for the regulation of indoor temperature and humidity [8, 78-126]. This is mainly caused by the porosity of hempcrete, which allows the transfer of water vapor with the surrounding air [8, 78-126]. This phenomenon occurs at times of high humidity, allowing the vapor to condense back into the liquid state and coming to rest on the surface of the pores [8, 78-126]. This process can be reversed in times of low humidity, essentially acting as a natural humidifier [8, 78-126]. Consequently, this has an interesting effect on the thermal conductivity of hempcrete [8, 78-126]. Hempcrete locks CO_2 within its fibers, has low thermal conductivity, and exceptional acoustic performance and vapor permeability, which regulates the temperature inside structures [8, 78-126].

Hempcrete has been one of the most researched building materials in recent times [8, 78-126]. The increasing use of conventional building materials in the country is increasing the risk of the catastrophic level of pollution in India [8, 78-126]. This needs to be halted at all costs to ensure that future generations are able to live a clean and healthy life in India [8, 78-126]. The Himalayan Hemp Organization, India are making people aware of the harm of using conventional building materials while at the same time educating them on the massive benefits of building with industrial hemp fiber, hempcrete [8, 78-126]. Hempcrete is a lightweight concrete, made from hemp pulp (or shiv), and hydraulic or aerated lime [8, 78-126]. It is typically used for timber frame infill, roofing tiles, insulation, renders, and floor slabs [8, 78-126]. Although hempcrete cannot provide enough structural integrity to be used as a load-bearing material [8, 78-126]. In the construction phase, hempcrete is the most commonly used for a timber frame infill, which is built using a removable formwork mold, such as a plastic casing [8, 78-126]. The most complicated process of the mixture design is getting the correct ratio between the fluid phases, air, water, the solid phases, hemp shiv and the binder [8, 78-126]. For instance, an example of a walling application would include 100 liters of hemp shiv, 22 kg of Tradical ® PF70 lime, and 30-35 kg of water [8, 78-126]. There is an urgent need for sustainable construction materials that can replace the traditional concrete used for building houses by using an eco-friendly alternatives, 'Hempcrete' [8, 78-126]. Furthermore, when new buildings in Uttarakhand state, India are constructed from industrial hemp, thereby increasing the income of hemp farmers in the Uttarakhand state, India [9, 78-126]. It will also facilitate proper waste management [8, 78-126]. Uttarakhand state, India can also reduce its dependence on other states by creating building materials out of local waste from hemp [8, 78-126]. Industrial *Cannabis sativa* (Hemp or fiber) plant material is light, keeps the room cool in summer and warm during winter [8, 78-126]. Industrial *Cannabis sativa* (Hemp or fiber) when mixed with lime, it becomes fire resistant and is also antibacterial and antifungal and can last centuries [89, 78-126]. Therefore, the youth of Uttarakhand state, India has taken a shine to the commercial usefulness of industrial hemp [8, 78-126]. They also market hemp-based products online [8, 78-126]. Hemp regulates moisture and reduces seepage. Industrial *Cannabis sativa* (Hemp or fiber) also has the ability to absorb carbon dioxide and improves air quality inside the building [8, 78-126].

Namrata, a resident of Kandwal village of Yamkeshwar block in Uttarakhand state, India founded her start-up Gohemp Agro Ventures, which researched the Industrial *Cannabis sativa* (Hemp or fiber) [8, 78-126]. The company manufactures daily used products from the seeds and fibre of hemp [8, 78-126]. The oil from hemp seed is used to make medicine [8, 78-126]. Namrata and team has focussed on making construction material out of Industrial *Cannabis sativa* (Hemp or fiber) [8, 78-126]. Further Go-hemp Agro Ventures decided to use Industrial *Cannabis sativa* (Hemp or fiber) as a source of employment for people living in the mountains [8, 78-126]. This would not only change the attitude of the people towards Industrial *Cannabis sativa* (Hemp or fiber) [usually associated with Medical *Cannabis sativa* [(marijuana or drug type), Charas, Ganja and drugs] but also prevent migration to cities from mountain villages [8, 78-126].

In another major development, Namrata Kandwal's Gohemp Agro Ventures, researched the applications of Industrial *Cannabis sativa* (Hemp or fiber) as an eco-friendly building construction material [8, 78-126]. Gohemp Agro Ventures have created a durable construction material out of hemp, which has also been used in **Ellora Caves** [8, 78-126]. **Ellora caves** in Maharashtra's Aurangabad district and Kandwal village in Uttarakhand's Pauri district binds the two, because of the Industrial *Cannabis sativa* (Hemp or fiber) [8, 78-126]. Further architect Namrata Kandwal of Uttarakhand and her team, who have used a hemp mixture in building construction and made it to the top five at the recent Global Housing Technology Challenge-India. Namrata and team has come up with building insulation material prepared by mixing hemp wood, lime and a variety of minerals [8, 78-126]. This mixture is very similar to what has been used in the Ellora caves, which date back to the 6th and 11th centuries AD, and the reason for its longevity [8, 78-126].

India's hemp industry is growing at a steady pace. Hempcrete is a popular, much-talked-about hemp product[8, 78-126]. In fact, many have lauded the Uttrakhand state, Indian couple who built an "all-green" house using hempcrete. As the climate conditions continue to change around the world, experts are looking for sustainable solutions [8, 78-126]. Further, hempcrete offers a number of benefits towards this goal [8, 78-126]. Hemp has eco-friendliness, low carbon footprint, thermal regulation, and moisture-absorbing properties. Industrial hemp fiber is an ecologically and financially sensible solution, especially in a climatically diverse country like India. It can be used to build, renovate, and/or restore all types of buildings—from houses and apartments to public sector buildings [8, 78-126]. Hempcrete is versatile and the fact is that it can be made by mixing lime and hemp hurds in proportions adapted to the work to be done [8, 78-126].

Hempcrete is eco-friendly and energy-efficient. The hemp plant is typically grown for either fiber or seed [8, 78-126]. In either case, the hurd is considered to be a by-product [8, 78-126]. Large-scale hemp production can therefore, generate tons of hurd for the construction and insulation markets[8, 78-126]. Hempcrete's unique ability to store energy and release it at a slow rate to stabilize temperature fluctuations makes it the ideal building material for all Indian weather conditions [8, 78-126]. Industrial *Cannabis sativa* (Hemp or fiber) hurds are able to store considerable amounts of moisture because of their porous structure [8, 78-126]. This moisture gets absorbed into the large internal surface area of the Industrial *Cannabis sativa* (Hemp or fiber) plant and moves to the cellular structure [8, 78-126].). This storage capacity allows hempcrete to absorb moisture when it exists and release it when conditions allow [8, 78-126]. On the other hand, the presence of lime, which is an inherently antimicrobial and antifungal compound, proves to be useful by creating a surface that resists mold in high temperature and humidity conditions [8, 78-126]. This resilience gives hempcrete an edge over other insulation materials, making it a desirable choice in both hot and cold climates as well as anywhere where humidity levels are high. India's average humidity levels go as high as 70% in the north, 81% in the east, 79% in the south, and 76% in the west[8, 78-126]. Therefore, Industrial *Cannabis sativa* (Hemp or fiber) is the right plant based building construction material that is hempcrete in India[8, 78-126].

Timber is an obvious example, as is bamboo. But there is another fast-growing crop hemp that makes an excellent building material and it is none other than hempcrete [8, 78-126]. Over the last few years, several hemp innovations have emerged. Industrial *Cannabis sativa* (Hemp or fiber) has been used to produce a lightweight building material for walling and insulation purposes [9, 78-126]. This has the added benefits of superior thermal performance and carbon negativity; plastic for functions ranging from single-use to automotive components; textiles used for technical as well as apparel [8, 78-126]. Furthermore hempcrete is found to be several times more sustainable than cotton and cheaper to produce [8, 78-126]. Hempcrete is a bio-composite made of the inner woody core, hurd of the hemp plant mixed with a lime-based binder [8, 78-126]. The hemp core or "Shiv" has a high silica content which allows it to bind well with lime [8, 78-126]. This property is unique to hemp among all natural fibers [8, 78-126]. The result is a lightweight cementitious insulating material weighing about a seventh or an eighth of the weight of concrete. Fully cured hempcrete blocks float in a bucket of water. It is not used as a structural element, only as insulating infill between the frame members though it does tend to reduce racking [8, 78-126].

Another entrepreneur Gaurav Dixit, who is CEO of GoHemp Agro Ventures Pvt. Ltd and general secretary of Uttarakhand Hemp Association (UHA), India is a non-profit organization found by the people from Uttarakhand state, India to help the state in the implementation of its Industrial *Cannabis sativa* (Hemp or fiber) vision at the grass-root level [8, 78-126]. Uttarakhand Hemp Association (UHA), India created a sustainable ecosystem of the hemp industry in Uttarakhand state, India which will benefit everyone associated with the hemp revolution especially the people directly connected to industrial hemp cultivation [8, 78-126]. Uttarakhand Hemp Association (UHA), India can integrate Industrial *Cannabis sativa* (Hemp or fiber) in future housing projects as the hemp house gives the privilege to live in a place that is not only safe and non-toxic but also helps in cleaning the air, and the earth [8, 78-126]. Industrial *Cannabis sativa* (Hemp or fiber) being a cellulose material takes carbon in during its life and lets it back into the atmosphere when it decays [8, 78-126]. The hemp plant is put it into a wall, the carbon is trapped inside and not released into the atmosphere [8, 78-126].

3. Advantages of Hempcrete

- Hempcrete meets condition of eco-friendly material and is made of renewable resources [8, 78-126]. Production is less energy-intensive. It has negative greenhouse gas emissions [8, 78-126]. It provides resistance and durability construction and healthy living condition. This material is recyclable. It is proposed to undertake a LCA (Life Cycle Assessment) of hempcrete in the future [8, 78-126].
- Hempcrete does not require agrochemicals like the common endosulfans, DDT's, and other nitrogenous fertilizers in its cultivation. The hemp plant absorbs up to 15 tonnes/hectare of carbon dioxide from the air, thus reducing the greenhouse gas effect on the planet [8, 78-126].
- Hempcrete brick or blocks are very light in weight and they are delivered to the building construction sites. Further much of the drying of hempcrete is already done, leading to a curing process that is sustainable as the blocks are left out to dry naturally without energy consumption [8, 78-126].
- Hempcrete as a green material promotes the wellbeing and safety of the public and minimizes the impact of climate change whilst maintaining the efficiency and resilience of buildings [8, 78-126].
- Transporting hempcrete is more economical compared to concrete, as it is a lightweight and low-density material. Furthermore, construction with hempcrete (as opposed to normal weight concrete) requires shallower [8, 78-126]. Thus more affordable foundations without necessarily requiring joints because of their distinctive properties [8, 78-126].
- Hempcrete has shown that hempcrete can absorb more carbon than it releases during its production phase, hence having negative embodied carbon [8, 78-126]. An average hempcrete apartment absorbs 7.5 tons of carbon dioxide, which is equivalent to the energy consumed by an average concrete apartment for heating and cooling in five years [8, 78-126]. A comparative life-cycle analysis by Florentin *et al*. (2017) suggests that hempcrete's net carbon balance is 10% less than that of autoclaved aerated concrete (1-50). Overall, hempcrete is carbon negative which signifies Earth's total net carbon savings [8, 78-126].
- Hempcrete walls have a high degree of sound insulation by trapping sound waves, thus reducing noise pollution [8, 78-126].The acoustical performance of hempcrete is highly dependent on parameters like thickness and whether or not hempcrete is rendered [8, 78-126].
- Hempcrete costs less than other synthetic insulation materials, which can compensate for the larger thickness of hempcrete walls [8, 78-126].
- The thermal storage capacity of hempcrete allows it to store the generated interior heat and release it to the interior later (e.g., at night) when outside is colder (during winter). On the other hand, during the summer, it will absorb the outside heat and does not release it to the interior immediately [8, 78-126].This will help to avoid overheating, and therefore can reduce energy bills [8, 78-126].
- Hempcrete also helps energy saving as its airtightness due to being a monolithic and single layer (solid) material. This will reduces heat loss through air leakage commonly seen with excessively large amounts through conventional wood-frame walls [8, 78-126].
- An ideal insulation material would be renewable and durable, which can be produced from waste streams or as a byproduct of other processes [8, 78-126]. Hempcrete has much of such attributes, besides the potential of creating healthy buildings. Hempcrete's construction flexibility allows architects and builders to come up with customized designs [8, 78-126].
- Hempcrete has high levels of cellulose. Hemp plants and hurds are composed of 65%– 70% and 40%–48% of cellulose, respectively [8, 78-126]. The high levels of cellulose prevent carbon from releasing into the atmosphere [8, 78-126].

4. Disadvantage of Hempcrete

Some drawbacks to the use of hempcrete include its capacity to retain water, which can cause swelling and bio-decay of the material, as well as poor mechanical performance which currently prevents it from use as a load bearing material [8, 78-126]. Despite its many benefits, hempcrete does have several key drawbacks that make it less than ideal as a building material [8, 78-126]. For instance, the porous structure of the hempcrete decreases its mechanical performance, and increases its ability to retain water [8, 78-126]. Though these issues are not a big problem as to prevent the use of hempcrete within the construction sector which provide strong limitations regarding what it can be used [8, 78-126]. The most significant setback of hempcrete is its poor mechanical performance, which prevents hemp from being used as a load-bearing material [8, 78-126]. This is primarily due to the fact that hempcrete is highly porous, causing a poor adhesion to the lime binder that results in an Elastic-like behaviour [8, 78-126]. Theoretically, this can be a useful trait in some situations, such as earthquakes, in which the material can bend without compromising its structure or cracking [8, 78-126]. On the other hand, it does cause hempcrete to deform a significant amount under stress [9, 78-126]. One good news is that recent experimentation has indicated that this can be avoided [8, 78-126]. In addition to poor mechanical performance, hempcrete also has a high capacity to absorb and retain water [8, 78-126]. This can be of benefit to the agricultural process, in that it decreases the irrigation requirements of the hemp crop, it can be a significant detriment to its use as a construction material [9, 78-126]. For instance, the hemp shiv is able to absorb up to 300-400 times its weight in water. A recent study utilized a recycled high-density polyethylene (rHDPE) in order to increase the mechanical strength of hempcrete [8, 78-126]. Following an alkali treatment, which consisted in dousing the hemp fiber in a 5% NaOH solution, the material was then coated with the polyethylene composite, resulting in an increased surface coarseness and surface area [8, 78-126]. This is allowed for greater adhesion to the binder [8, 78-126]. However, some research asserts that the mechanical performance can be increased, depending on what binder is used. More recently, research has been conducted on a building material utilizing hemp known as hemp lime concrete or hempcrete [8, 78-126].

Since then, much research has been carried out regarding the mechanical properties of hemp reinforced concrete as well as the different binder mixes that may be used [8, 78-126]. A study by de Bruijn et al. (2009) examined the effect of varying the proportions of hydrated lime, hydraulic lime, and Portland cement [8, 78-126]. The composition of the hemp used by weight was 35% fibres, 62% shives (hurds), and 4% dust [8, 78-126]. Hempcrete has been shown to quickly reach steady state temperatures within a test wall and has a wider variation in relative humidity when compared to more conventional materials such as aerated autoclaved concrete and vertically perforated brick [8, 78-126]. More research will be required to study how the moisture migration occurs [8, 78-126]. The power consumption of the hempcrete building was relatively close to that of the fibreglass building [8, 78-126]. The hempcrete building is not as airtight as the fibreglass building [8, 78-126].

Hempcrete is a useful material for reducing the impact on the construction sector has on the environment, while retaining good economic value [8, 78-126]. Although, with the current methods of application, hempcrete is not an ideal material for construction, it does present many characteristics that set it apart from traditional concrete in terms of economic and environmental benefits [8, 78-126]. The material's density provides airtightness, guaranteeing uniformity within the structure [8, 78-126]. In contrast, it is argued that these hempcrete walls are too thick, subsequently leaving residents with less carpet space [8, 78-126]. Hemp is not readily available everywhere and is even illegal in a few countries, so procuring the material for construction can be difficult or expensive. There is a process that one has to go through to earn a permit application for a hempcrete building[8, 78-126]. It starts off with the applicant understanding the local code while taking into consideration the parts of the building that do and do not meet that specific code [8, 78-126].

Recycling is also an option to get rid of hempcrete building once it reaches the end of its life [8, 78-126]. However, hempcrete is still a relatively new material and not many hempcrete buildings have been built to **reach** their end of life[8, 78-126]. So, while R&D efforts are still ongoing for the efficient recycling of hempcrete, landfill disposal is currently the best option with the caveat that the disposed hempcrete will not emit carbon dioxide when decomposed [8, 78-126]. Hempcrete showed lower thermal diffusivity when compared to other materials like concrete, earth block, and solid brick [8, 78-126]. The hemp shiv contains air spaces between its particles and microscopic pores within the material itself, which provide thermal resistance, i.e., the more air pockets, the higher the insulation [8, 78-126]. Life cycle assessment (LCA) can comprehensively analyze the sustainability of a hempcrete building's material composition in terms of embodied energy, the effect of waste products during manufacturing and construction processes, as well as any material restoration over the building's lifetime [8, 78-126]. The life span of hempcrete is not accurately known. However, the lifecycle assessments performed on the material estimated the lifespan of hempcrete walls to be around 100 years with hardness and rigidity increasing over time [8, 78-126].

Although hempcrete homes can save on electricity, their construction is currently more expensive compared to the conventional wood frame with fiberglass batt insulation [8, 78-126]. Because hempcrete building construction is relatively new, not enough research and development (R&D) has been conducted on industrial hemp and hempcrete usage to lower the cost [8, 78-126]. However, as with any other innovative product, with more use and sales of the product, more economical options will evolve. Needless to say, more R&D can help hempcrete to be accepted by the builders [8, 78-126]. The lack of architects, engineers, builders with an interest in hempcrete, and the current knowledge gaps require more training programs for design professionals and builders [8, 78-126]. In the long run, this will help to lower the costs. Looking ahead, further research on increasing the mechanical capabilities and decreasing the water absorption will go a long way toward unlocking the potential of hemp as a sustainable building material [8, 78-126]. As mentioned earlier, there are no hempcrete constructions in India that are validated by scientific investigations to prove its suitability for adoption by the Indian consumers [8, 78-126]. Even the most basic material characteristics of hempcrete when manufactured in India are not determined [8, 78-126]. Needless to say, the manufacturing processes are not standardised either, resulting in inconsistent hempcrete material behaviour [8, 78-126].

An architect couple has built a sprawling 5-room house in Yamkeshwar block of Pauri Garhwal district, Uttarakhand state, India using ‘hempcrete’ – a mixture of parts of “bhang” or hemp plant, lime, wood, mud, water and other minerals – which can be used as a green alternative to concrete [8, 78-126]. This is the first time hempcrete has been used as a building construction raw plant material to build a house in India. This technique is prevalent in countries like USA, Canada, Australia and New Zealand [8, 78-126]. Hempcrete is at a great disadvantage since it is not suitable for being a load-bearing material like concrete. However, its ability to resist fire, mold, fungus, and moisture along with its carbon-negative properties compensates for that. Seeing a shift in the global selection of concrete as a building material to utilizing hempcrete will be contingent on costs, hemp availability, awareness, and project suitability [8, 78-126]. Therefore, in detail experimental study is warranted for the commercialization of hempcrete as a building material. Finally, the future of the Industrial *Cannabis sativa* (Hemp or fiber), strongly depends on market demand for its bio-based products that will help the plant to establish itself as a worthy sustainable crop[8, 78-126].

5. What is 3D Printing and Applications

3D printing, also known as additive manufacturing, is a method of creating a three dimensional object layer-by-layer using a computer created design [44-77]. 3D printing or additive manufacturing is a process of making three dimensional objects from a digital file [44-77]. The creation of a 3D printed object is achieved using additive processes. In an additive process an object is created by laying down successive layers of material until the object is created [44-77]. Each of these layers can be seen as a thinly sliced cross-section of the object. There is one exception though, and it’s called volumetric 3D printing. With volumetric printing entire structures can be formed at once without the need for layer-by-layer fabrication [44-77]. It is worth noting, however, that as of now, volumetric technology is primarily in the research phase [77]. 3D printing is an additive process whereby layers of material are built up to create a 3D part [77]. Building on Ralf Baker's work in the 1920s for making decorative articles (patent US423647A), Hideo Kodama's early work in laser cured resin rapid prototyping was completed in 1981 [77]. His invention was expanded upon over the next three decades, with the introduction of stereolithography in 1984 [77]. Chuck Hull of 3D Systems invented the first 3D printer in 1987, which used the stereolithography process [77]. Charles Hull is the inventor of stereolithography, the first commercial rapid prototyping technology commonly known as 3D printing [44- 77]. Chuck Hull is an American inventor who is the co-founder, executive vice president and chief technology officer for regenerative medicine of 3D Systems [77]. He is one of the inventors of the SLA 3D printer, the first commercial rapid prototyping technology, and the widely used STL file format [44- 77]. Hideo Kodama of Japan is created with the first 3D printing patent in 1981 [77]. **Chuck Hull**, an American inventor, is often regarded as the “**Father of 3D Printing** [77]. Hull developed the stereolithography fabrication system in 1984, which remains a foundational technology in 3D printing today [77]. The first documented iterations of 3D printing can be traced back to the early 1980s in Japan [77]. In 1981, **Hideo Kodama** was trying to find a way to develop a rapid prototyping system. He came up with a layer-by-layer approach for manufacturing, using a photosensitive resin that was polymerized by UV light [44-77]. Although Kodama was unable to file the patent requirement of this technology, he is most often credited as being the first inventor of this manufacturing system, which is an early version of the modern SLA machine[77]. Across the world a few years later, **a trio of French researchers** was also seeking to create a rapid prototyping machine. Instead of resin, they sought to create a system that cured liquid monomers into solids by using a laser [77]. Similar to Kodama, they were unable to file a patent for this technology, but they are still credited with coming up with the system [77]. That same year, **Charles Hull**, filed the first patent for Stereolithography (SLA) [44-77]. An American furniture builder who was frustrated with not being able to easily create small custom parts, Hull developed a system for creating 3D models by curing photosensitive resin layer by layer [77]. This was followed by developments such as selective laser sintering and selective laser melting, among others [77]. Other expensive 3D printing systems were developed in the 1990s-2000s, although the cost of these dropped dramatically when the patents expired in 2009, opening up the technology for more users [44-77].

There are three broad types of 3D printing technology; **sintering**, **melting**, and **stereolithography** [77]. S**intering** is a technology where the material is heated, but not to the point of melting, to create high resolution items [77]. Metal powder is used for direct metal laser sintering while thermoplastic powders are used for selective laser sintering[44-77]. **Melting** methods of 3D printing include powder bed fusion, electron beam melting and direct energy deposition, these use lasers, electric arcs or electron beams to print objects by melting the materials together at high temperatures [44-77]. S**tereolithography** utilises photopolymerization to create parts[77]. This technology uses the correct light source to interact with the material in a selective manner to cure and solidify a cross section of the object in thin layers [77]. Types of 3D printing: 3D printing, also known as additive manufacturing, processes have been categorized into seven groups by ISO/ASTM 52900 additive manufacturing - general principles - terminology [44-77]. All forms of 3D printing fall into one of the following types. 1) Binder Jetting. 2) Direct Energy Deposition. 3) Material Extrusion 4) Material Jetting 5) Powder Bed Fusion 6) Sheet Lamination 7) VAT Polymerization [77]. An STL file is a simple, portable format used by computer aided design (CAD) systems to define the solid geometry for 3D printable parts[77]. An STL file provides the input information for 3D printing by modeling the surfaces of the object as triangles that share edges and vertices with other neighboring triangles for the build platform [77]. The resolution of the STL file impacts the quality of the 3D printed parts - if the file resolution is too high the triangle may overlap, if it is too low the model will have gaps, making it unprintable [44-77]. Many 3D printers require an STL file to print from, however these files can be created in most CAD programs [44-77].

6. 3D Printing Advantages

- This technology allows for the easy creation of bespoke geometric parts where added complexity comes at no extra cost. In some instances, 3D printing is cheaper than subtractive production methods as no extra material is used [44-77].
- Since no moulds are required, the costs associated with this manufacturing process are relatively low. The cost of a part is directly related to the amount of material used, the time taken to build the part and any post processing that may be required [44-77].
- Because the process is based upon computer aided designs (CAD), any product alterations are easy to make without impacting the manufacturing cost [44-77].
- Because the technology allows for small batches and in-house production, this process is ideal for prototyping, which means that products can be created faster than with more traditional manufacturing techniques, and without the reliance on external supply chains [44-77].
- Although plastics and metals are the most common materials used in 3D printing, there is also scope for creating parts from specially tailored materials with desired properties. So, for example, parts can be created with high heat resistance, water repellency or higher strengths for specific applications [44-77].

7. 3D Printing Disadvantages

- Can have a lower strength than with traditional manufacture: While some parts, such as those made from metal, have excellent mechanical properties, many other 3D printed parts are more brittle than those created by traditional manufacturing techniques. This is because the parts are built up layer-by-layer, which reduces the strength by between 10 and 50% [77].
- Increased cost at high volume: Large production runs are more expensive with 3D printing as economies of scale do not impact this process as they do with other traditional methods. Estimates suggest that when making a direct comparison for identical parts, 3D printing is less cost effective than CNC machining or injection moulding in excess of 100 units, provided the parts can be manufactured by conventional means[77].
- Limitations in accuracy: The accuracy of a printed part depends on the type of machine and/or process used. Some desktop printers have lower tolerances than other printers, meaning that the final parts may slightly differ from the designs. While this can be fixed with post-processing, it must be considered that 3D printed parts may not always be exact[77].
- Post-processing requirements: Most 3D printed parts required some form of post-processing. This may be sanding or smoothing to create a required finish, the removal of support struts which allow the materials to be built up into the designated shape, heat treatment to achieve specific material properties or final machining[77].

The printing time depends on a number of factors, including the size of the part and the settings used for printing [77]. The quality of the finished part is also important when determining printing time as higher quality items take longer to produce. 3D printing can take anything from a few minutes to several hours or days - speed, resolution and the volume of material are all important factors [44-77]. Due to the versatility of the process, 3D printing has applications across a range of industries, for example: Aerospace 3D printing is used across the aerospace (and Astros pace) industry due to the ability to create light, yet geometrically complex parts, such as blisks. Rather than building a part from several components, 3D printing allows for an item to be created as one whole component, reducing lead times and material wastage[44- 77]. The automotive industry has embraced 3D printing due to the inherent weight and cost reductions[77]. It also allows for rapid prototyping of new or bespoke parts for test or small-scale manufacture[77]. So, for example, if a particular part is no longer available, it can be produced as part of a small, bespoke run, including the manufacture of spare parts. Alternatively, items or fixtures can be printed overnight and are ready for testing ahead of a larger manufacturing run[44-77]. The medical sector has found uses for 3D printing in the creation of made-to-measure implants and devices. For example, hearing aids can be created quickly from a digital file that is matched to a scan of the patient's body. 3D printing can also dramatically reduce costs and production times[77]. The rail industry has found a number of applications for 3D printing, including the creation of customized parts, such as arm rests for drivers and housing covers for train couplings [77]. Bespoke parts are just one application for the rail industry, which has also used the process to repair worn rails. Robotics: The speed of manufacture, design freedom, and ease of design customization make 3D printing perfectly suited to the robotics industry[44-77]. This includes work to create bespoke exoskeletons and agile robots with improved agility and efficiency [77]. 3D printing encompasses many forms of technologies and materials as 3D printing is being used in almost all industries. It is important to see it as a cluster of diverse industries with a myriad of different applications [44- 77]. A few examples: – consumer products (eyewear, footwear, design, furniture) – industrial products (manufacturing tools, prototypes, functional end-use parts) – dental products – prosthetics, – architectural scale models & maquettes – reconstructing fossils, – replicating ancient artefacts – reconstructing evidence in forensic pathology and – movie props [44-77]. 3D printing also utilized in the production of children's toys of different shapes, designs and creates a fun games [44- 77].

3D printing is important for the many benefits it brings [44- 77]. It allows users to produce items that have geometries which are difficult or impossible for traditional methods to produce. It also allows users with a limited experience to edit designs and create bespoke, customized parts [44-77]. On-demand, 3D printing also saves on tooling costs and provides an advanced time-to-market [44- 77]. 3D printing is important for industries such as aerospace, where it can create lightweight yet complex parts, offering weight saving, the associated fuel reductions and a better environmental impact as a result. It is also important for the creation of prototypes that can advance industry[77].

3D printing has the capability to disrupt traditional manufacturing through the democratisation of production along with the production of moulds, tools and other bespoke parts [44- 77]. However, challenges around mass production mean that 3D printing is unlikely to replace traditional manufacturing where high volume production of comparatively simple parts is required [44- 77]. 3D printing fumes can be dangerous to health as the process produces toxic filament fumes. These emissions are produced as the plastic filaments are melted to create the product layer-by-layer. However, correct procedures such as ensuring sufficient ventilation or using extractors can solve this issue [77]. Furthermore, there are ongoing advancements in the world of additive manufacturing, including 4D and 5D printing [77]. While 3D printing focuses on creating three-dimensional objects layer by layer, 4D printing adds the element of time to the process [77]. In essence, the printed objects can self-assemble or change shape in response to external factors like temperature or moisture after they have been created [77]. On the other hand, 5D printing involves a more advanced approach that centers around optimizing material usage and building structures with increased strength and reduced weight [44-77]. This is achieved by utilizing highly precise multi-axis machines, able to print objects in a more intricate manner than conventional methods [77]. These cutting-edge technologies promise to revolutionize various industries by offering new possibilities for product design and functionality. It is an exciting time as researchers continue exploring the full potential of these innovative manufacturing techniques [44-77].

8. 3D Printed Hempcrete based Building Construction

Hempcrete is being called an ideal solution for environmentally friendly building by some in the green building movement [8, 44-72]. Made from a mixture of hemp fiber and lime, the lightweight material has many benefits, including its strength, lack of toxins, its imperviousness to mould and pests, durability, and lack of flammability [8, 44-72]. Besides its new use in hempcrete, the hemp plant has been used for centuries in the manufacture of rope, sails, clothing and paper, among others [8, 44-72]. It also sequesters carbon dioxide and keeps it out of the environment[8, 44-72]. As a building material, hempcrete hardens over time, as the lime absorbs more carbon dioxide from the atmosphere, causing it to petrify. According to Knutsen, this property will make it last longer without needing expensive repairs. In one of the research study, Chad Knutsen has submitted a proposal to the Massachusetts Institute of Technology's Climate CoLab in which he proposes to construct a building entirely of 3D printed hemp materials[8, 44-72]. The materials will include hemp fibreboard, hempcrete bricks and hemp-derived resin and plastic composites [8, 44-72]. Knutsen's proposal states that all of the materials will be produced in "single-man-manageable blocks [8, 44-72]. Knutsen and his team claim that replacing conventional concrete with hempcrete would reduce CO_2 emissions by 7–8 per cent worldwide[8, 44-72].

Hempcrete is a bio-based building material that is becoming more popular nowadays and is made up of lime-based binder and bio-based filler – hemp shives, an agricultural by-product resulting from hemp fibre processing. It is used as a self-bearing envelope and thermal insulation material and has a low environmental impact [8, 44-73], especially CO_2 emissions, as they have been sequestered during the growth of the hemp plants [8, 44-73]. Additional CO_2 is also absorbed during the hardening of the lime binder, as it hardens by carbonation, absorbing part of the CO_2 emitted during the production process and thus reducing total emissions [8, 44-73], The hygrothermal properties of hempcrete provide both indoor comfort and good thermal performance, which is also important in assessing the sustainability of the material [8, 44-73]. Hemp concrete offers low thermal conductivity from 0.06 to 0.13 W/(m·K), high vapor permeability ~ 10–11 – 10–10 kg/(m·s·Pa) and good moisture buffering with moisture buffering value (MBV) > 2 [8, 44-73].

Currently, hemp is being used in 3D printing textiles, rope, and biofuel. Similar to jute in its durability, hemp, although from a different source has similar 3D printing properties [44-71-130]. Hemp can be used in block form or poured like traditional concrete using hempcrete, a combination of lime, hemp fibers and a chemical binder. Panels made of hemp can also be used [44- 1- 71]. The 3D printing industry has been integrating hemp into its technology. Hemp can be transformed into filament to be used for 3D printing. Biodegradable, recyclable and free from toxins, it can replace petroleum-based plastics[44- 50- 71]. The material has a higher impact resistance than regular PLA. Bioplastic made using hemp is fully biodegradable and compostable. It also makes an odorless print material and, compared to other materials, it has better technical characteristics. In a March 1st, 2023, article in The New York Times, titled "For Green Materials, Builders Turn to Hemp," the topic of hemp as a viable substitute for construction materials was covered [71]. This is being taken very seriously as the Pierre Chevet Sports Hall, in Croissy-Beaubourg, located on the outskirts of Paris, was the first commercial project in France to be constructed almost entirely with hemp construction blocks [44-71]. One solution under investigation for supplementing this increased demand in materials is natural fiber reinforced 3D printable concrete (NFR3DPC) [44- 75]. 3DPC technologies have shown to reduce up to 60% of construction waste, 70% of production time, and 80% of the associated labor costs [44-75]. The implementation of natural fibers into 3DPC could help to further reduce the impact of such practices, by providing locally sourced reinforcement for the cementitious composites [44-75]. Local material sourcing reduces the associated CO_2 emissions produced by material transportation as well as offers localized financial supplementation to the surrounding communities[44-75]. Hemp fibers have been selected as the reinforcing natural fiber. Industrial hemp (*Cannabis sativa* L.) is a resilient fibrous plant that offers significant CO_2 sequestration properties, soil remediation benefits, high fiber yields, and comparable fiber mechanical properties to that of synthetic fibers [44-75]. Additionally, the production of natural fibers consumes 60% less energy than the manufacturing of glass fibers providing the potential to significantly reduce the embodied energy required for reinforcing fiber production [44-75]. Therefore, the development of hemp fiber reinforced 3DPC (HFR3DPC) is aimed to reduce the embodied carbon emissions and energy consumption of the construction industry[75].

Ceylon et al., (2024) [51] are of the opinion that interest in natural fiber reinforced polymer composite materials is growing rapidly in industrial applications and scientific research [51-57]. In terms of sustainability and reducing environmental damage, natural fibers are preferred for widespread application because they are abundant in nature, are fully or partially biodegradable, have low costs, and are an ecological alternative with satisfactory mechanical properties compared to synthetic fibers such as glass fibers [51]. Using natural fibers allows for less extraction power and greener, sustainable, and smarter construction development than polymer/steel/synthetic fibers[51-57-77]. Cellulosic fibers such as hemp, flax, jute, sisal, coir, bamboo, banana, kenaf, and ramie are used as reinforcement in natural fiber-reinforced polymer composites (NFRPCs) and are abundant in many countries [51-77]. Lignocellulosic fibers such as jute, sisal, flax, and hemp have been reported to be an alternative to glass-fiber and carbon-fiber reinforced composites in various applications. In addition, natural fiber-reinforced polymer composites (NFRPCs) have better electrical and higher fracture resistance [51-77]. When it comes to hemp fiber, it is known to have a 3–9 times faster growth rate than other plants and a higher CO_2 absorption capacity than any other plant. In addition, it can be planted in various areas and requires very little fertilizer and herbicides (pesticides), grows very fast, yields more fiber per acre compared with kenaf and flax [51-77]. Therefore, using hemp fiber for natural fiber-reinforced polymer composites (NFRPCs) will create a greener and more sustainable alternative, and the damage to nature will be minimized [51]. According to studies in the literature, it has been determined that cumulative energy is reduced by 41–64% in the production of polymer-based materials produced with 3D printers [51-77].

In 3D printing, i.e., additive manufacturing (AM), the designed parts are produced in layers, rather than subtracting from a larger part [51]. One of the production techniques used in AM technology is fused filament fabrication, which is obtained by extruding thermoplastic or wax material from a heated nozzle[51]. Other manufacturing techniques include jetting a binder into a polymeric powder, using an ultraviolet laser to harden a photosensitive polymer, and using a laser to melt polymeric powder (Laser Sintering) [51]. Additive manufacturing enables more efficient and sustainable production processes. During production, only the amount of material is used that is also required to manufacture the printed end-product[51-76]. Thus, no or only little unnecessary resource consumption remains for disposal. In addition to a more sustainable production, renewable and biodegradable raw materials from bio-based sources may also be used for various products in order to achieve sustainable production [44-71-77]. The additive manufacturing technology fused filament fabrication (FFF), a process in which a component is built up layer by layer through the deposition of material based on digital 3D design data [76], can be regarded as the most prominent additive manufacturing process. However, further technologies based on the deposition of fused thermoplastic polymers exist, such as laser-assisted FFF [76], electrohydrodynamic direct-writing [76] and direct sound printing[76-77].

The most used production type in AM technology is fused deposition modeling (FDM), and versatile structural parts can be produced with minimal waste material without the need for investments such as molds, huge machines, and excess staffing for rapid prototyping (RP) [51-57-77]. 3D printing is used to apply computer-aided design (CAD) files of 3D objects, which are digitally designed for use in different applications or obtained by scanning an existing object through therapeutic prototyping or rapid manufacturing[51-57-77]. Thanks to 3D printing technology, it is possible to create low-cost, rapid design solutions and applications and eliminate defects at early design stages [51-57-77]. 3D printed parts are characterized as anisotropic and depend on the direction of printing and raster angle. In addition, their mechanical properties and structural strength depend on many factors, such as extrusion speed, nozzle, bed temperature, and infill ratio [51-57-77-130]. The most used thermoplastic polymers in FDM technology are ABS, PLA, PC, and PET-G [51-57-77]. Considering the fiber-reinforced thermoplastics produced with FDM technology, ABS and PC have the best structural integrity and are used in many engineering applications where strength is important [51-77]. The fact that hemp fiber-reinforced PC composites are suitable for use in 3D printers will contribute to the concept of sustainability by reducing environmental damage [51-57-77-130].

9. Following are the few examples of 3D printed hempcrete materials used for the building construction

- The past decade has seen a notable increase in the interest in additive manufacturing (AM) [48], otherwise called three-dimensional (3D) printing, for rapid fabrication of complex-shaped structures for various applications [44-48]. However, the use of PLA is often limited by issues relating to its low stiffness and low thermo-mechanical stability. Different reinforcing materials, in special natural fibers, have been used to overcome these drawbacks [2,7–11]. It has been demonstrated that alkali-based treatments of natural fibers followed by a bleaching process improved fiber/matrix interfacial bonding and processability of the composites, which is highly beneficial for 3D printing applications [44, 45]. Alkaline treatments removed amorphous components from the biomass such as hemicellulose and hurd [44, 45]. Hemp hurd is a by product of hemp fiber production and its primary use has been as a filler in the form of particles for polymers or used in the formulations of hempcrete [8, 44-46].

One of the recent study by Beg et al., (2024) [44] reported that 3D printing filaments were produced from hemp hurd fibre-reinforced polylactide (PLA) composites [44]. Hemp hurd microfibers were obtained through alkaline digestion followed by a bleaching treatment and were used to produce PLA-based composites with 20–40 wt% fiber content for fused deposition modelling [44]. However, tensile strength was only improved for the 20 wt% formulation, with an increase of 8% in comparison with neat PLA [44]. Nevertheless, the thermo-mechanical properties of the composites were significantly enhanced with the addition of fibers [44]. In addition, physical objects were printed from the recycled filaments to assess their recyclability and printability. It was found that the recycled filaments maintained comparable mechanical properties and printability after three recycling cycles [44]. During this study of Beg et al., (2024) [44], air-dried hemp hurds were separated from hemp stems (1–1.5 m long) and then were cut into 2–3 cm lengths using a guillotine[44, 45]. Further the hurds were weighed and subjected to digestion in a mixed solution of sodium hydroxide and sodium silicate following the procedure described previously [44, 45]. After digestion, the hurd fibers were washed severally with water until the wastewater reached pH 7 and then the fibres were dried at 80° C in an oven for 48 h. Digested fibers were further bleached using a solution of H_2O_2 and $NaSiO_3$, following the procedure described in the literature [44]. After bleaching, a Sunbeam Multi grinder with blunt blades running at a high rotational speed was used to de-fib rate the fibers [44, 45].

On the basis of the study conducted by Beg et al., (2024) [44], composites were first produced from PLA and hemp hurd fibers at different fiber content (20 wt%, 30 wt%, and 40 wt%)[44]. The matrix and fiber were compounded twice using a TSE-16-TC twin-screw extruder with a screw speed setting of 100 rpm at a temperature profile in the range of 165–175° C [44]. The extrudate was pelletized into 3 mm pellets using a Moretto GR knife mill and dried in a vacuum oven set at 60° C for 2 h [44]. During filament production, the extrusion and spooling speeds were adjusted to produce filaments with a constant diameter of 1.75 ± 0.10 mm. Tensile testing samples were 3D printed according to ASTM D638 Type V specimens using a Maker Gear™ M2 desktop 3D printer [44]. The 3D printer was equipped with a Simplify 3D® software package for slicing the computer-aided design (CAD) files and controlling the 3D printer[44]. Samples were printed with a free-span nominal dimension of 3.18 mm, 1.50 mm, and 10.96 mm for width, thickness, and length, respectively [44]. The printing filaments were vacuum dried for 2 h at 50° C before printing, and samples were printed at a printing speed of 1800 mm/min, and a layer height of 0.1 mm using predetermined printing parameters[44]. After each recycling step, new filaments were re-produced using the filament extruder and tensile testing samples were printed using the 3D printer following the procedure described above [44]. A 3D printed object (vase) of the composite with 20 wt% fiber was also subjected to recycling in a similar manner as the filament [44].

On the basis of the study conducted by Beg et al., (2024) [44], composites were produced from PLA and hemp hurd fiber [44]. The reinforcing ability of hemp hurd fibers is demonstrated in this study [44, 45]. The recyclability study showed that as the number of recycling steps increased, there was an increasing possibility for fiber separation from the matrix [44, 45].

- In another study reported by Sultan et al., (2024) [49], additively manufactured polypropylene-hemp fibre (PPHF) composites, which were composed of polypropylene (PP) and hemp fibers (HF) in various percentages (5%, 10%, and 20%) was studied [49]. This study has examined the mechanical properties and water absorption behaviors of extruded PP, conventional filament PP and PPHF composites [49]. The results of this study showed that the 5% hemp PP composite exhibited the highest tensile strength, and the 20% hemp PP composite showed the highest Young's modulus [49]. Today, industrial hemp (*Cannabis sativa* L.) is produced all over the world, having been farmed for many centuries [1-49]. It is among the earliest plants that have been utilized to produce food, clothing, and medicine [1-49]. Various mechanical techniques are used to process plant stems to obtain the fiber [1-49]. Due to their higher specific strength and lower cost when compared to conventional reinforcements, hemp and flax fibres have recently been used by automotive manufacturers for producing non-structural components [1-49].

One of the most popular methods for creating prototypes and producing CAD-designed products is additive manufacturing [1]. It is widely employed in sectors like automotive, composites, healthcare and electronics [2]. It is an extremely practical method for creating inexpensive complex geometries of excellent quality. Along with the popular polymeric materials being used for 3D printing, nowadays more and more fiber-reinforced polymers are also being used for 3D printing [49]. Polymers reinforced with natural fibers are becoming more popular in 3D printing due to the numerous advantages they offer such as altering the mechanical properties of the polymer [49]. In fact, natural fiber-based composites are more recyclable than those reinforced with glass or carbon fibers [49]. The benefits of natural plant fibers over conventional glass fibers including superior specific strengths and modulus, low density, better energy recovery, decreased skin-related and respiratory irritation along with good biodegradability [49]. Plus, they are more economically viable [49].

According to the study reported by Sultan et al., (2024) [49], hemp originally was in the form of stalks. It was necessary to grind it in order to combine its shives with the polymers [49]. When stalks were grinded, smaller pieces of hemp fibers were produced still resulting in the clogging of the machinery when too much hemp was added all at once[49]. Hence it became necessary to use modest amounts and regularly remove hemp from the grinder. After the stalks had been grinded, shives of different dimensions were produced [49]. As a result, the grinded material was passed through a series of vibrating sieves with smaller openings of 2, 1, 0.5, and 0.125 mm [49]. The shives with sizes ranging from 1 to 2 mm were chosen [49]. Shives were covered in dust as a consequence of the grinding process, which is an undesired impurity in composites (the retted hemp batches were similarly covered with dirt) [49]. Hence shives were supposed to be washed before being combined with polymers because of this procedure and sieving [49]. They had been washed in a thinner sieve (so that none of them would pass through the holes) and the washing was stopped when the washing water was sufficiently clear[49]. The application of sodium hydroxide to hemp fibers causes the fiber bundles to separate and their surface roughness to increase [49]. So, some shives were additionally treated by soaking for 5 h in a 4.5 wt percent NaOH solution. The shives were dried in ovens at 80^{o} C for 24 h after washing or after soaking [49]. The main materials were polypropylene pellets, processed hemp fibres and minor amounts of maleic anhydride-grafted PP (MAPP) for better adhesion between PP and fibres [49]. The compatibilizer utilized in this study was MAPP, with a fixed quantity of 2% of the total composite material mass across all three composite materials [49]. This fixed amount may not have significantly influenced the properties. PP pellets were dried using a drying oven for 24 h to remove any moisture from them [49]. HF were washed with warm water in a strainer and then allowed to dry in the oven for 24 h at the temperature 80 ^{o} C before usage [49]. HF were grinded once again to make them even finer before mixing with PP[49]. MAPP was used at room temperature [49].

According to the study reported by Sultan et al., (2024) [49], an extruder is one of the best machines that can be used to mix two or more different materials. In this project, a Thermo Fisher Scientific Process 11 Parallel Twin-Screw Extruder with 3 mm die was used for the purpose of extrusion [49]. Firstly, pure PP pellets were extruded with a melting temperature of 215^{o}C, extruder rpm of 60 and melt flow pump rpm of 30 [49]. At first water cooling was given a try to be a potential option to cool the filament before winding on the spool but it was not working [49]. Therefore, instead, room temperature cooling on a conveyor belt along with a little bit of air cooling was adopted. After obtaining a spool of extruded PP filament, extrusion of composite materials was started, but the extrusion parameters were changed according to the complexity of the composite material [49]. For the extrusion of the composites melt temperature was kept constant, the rpm of the extruder was reduced to 40 as the mixture was quite dense and the rpm of the melt flow pump was reduced to 20 to get a uniformly mixed material [49].

The filament 3D printers available at the lab demanded a constant diameter of 2.8 mm which was very hard to attain even after several attempts [49]. Another critical issue was that the size of the nozzle of the 3D printing was 0.4 mm where the fibers can cause blockage in the nozzle. Alternatively, it was considered that a pellet 3D printer should be used to 3D print this composite material [49]. For that, all the filament spools were chopped into 2 mm pellets using a pelletizer [49]. Then 3D printing was initiated but the material was not sticking to the bed. To resolve that issue, the bed was taped with PP packaging tape which resulted in better adhesion as PP likes to stick to itself [49]. Printing speed was kept low as it can improve the adhesion of the material to the bed [22]. After 3D printing, a little bit of post-processing was done by griding irregular areas on the sides of the specimens [49]. The samples produced were quite decent in quality [49].

According to the study reported by Sultan et al., (2024) [49], reinforced hemp fibers (HF) with percentages (5,10 and 20%) into polypropylene (PP), to make various polypropylene-hemp fiber (PPHF) composite materials has been reported [49, 50]. The mechanical properties of extruded polypropylene (PP), in its original form and traditional PP filament available for 3D printing were compared to those of PPHF composites[49]. Five various materials were 3D printed extruded polypropylene (PP), filament PP and polypropylene-hemp fiber (PPHF) composites with (5,10 and 20%) hemp fibers inside them [49]. The extruded PP showed the highest flexural modulus and flexural strength as flexural properties are mostly polymer dependent. Filament PP showed the lowest flexural and tensile properties which means all the PPHF composites had better mechanical properties than that of traditional PP filament [49]. 5% hemp PP showed the highest tensile strength[49]. 20% hemp PP had the highest Young's modulus amongst all specimens [49]. Whereas 10% hemp PP exhibited the second highest value for Young's modulus[49]. These results highlight how crucial hemp fiber content is in producing materials with desirable properties [49]. Hemp fibers and PP work well together to provide sustainable, high-performance materials with specific mechanical characteristics for a range of industrial applications [49].

- Recently one of the study conducted by Ceylon et al., (2024) [51] investigated the properties of alkali-treated hemp fiber-reinforced polycarbonate (PC) composites that can be formed by 3D printers for architectural applications [51]. Further this study was used to determine the optimum alkali treatment to be applied to the fibres, the properties of the samples treated with 5% and 7% sodium hydroxide (NaOH) at both ambient temperature (AT) and 120 °C (HT) were determined by Fourier transform infrared spectroscopy (FTIR) and thermogravimetric analysis (TGA) [51]. It was determined that the alkali treatment that gave the optimum result was 5% HT[51].

According to Ceylon et al., (2024) [51] the experimental study was conducted in two stages. The first stage is described under the title 'Surface Treatment of Hemp Fibres,' the optimum alkali treatment to be applied to the fibres was determined by looking at their chemical and thermal properties using FTIR and TGA analysis[51]. The second stage is described under the title '3D printed composites', and PC/hemp composite samples with different ratios were produced by applying the specified alkali treatment[51]. Alkaline, silane, and acetylation chemical treatments were performed to overcome these disadvantages [51]. These chemical treatments improved the interfacial bonding between hydrophilic fibers and hydrophobic (water-avoidance) polymers, thereby reducing moisture uptake, increasing microbial degradation resistance, and extending durability [51]. Alkali treatment, or mercerization, is one of the most widely applied chemical treatments to natural fibers that reinforce thermoplastics [51]. As a result of the alkali treatment, the surface hardness is increased by removing the hydrogen bonding in the network structure [51]. In addition, substances such as lignin, wax, and oils on the fiber surface are removed, and the natural cellulose structure is depolymerized, resulting in short-length crystallites [51]. This way, the material's properties are improved by providing a better interfacial bond between the natural fibre and the thermoplastic matrix [51]. According to the literature, optimum results have been obtained from the alkaline treatment of hemp fiber with NaOH solution [51]. Therefore, in this study, NaOH was chosen for the alkali treatment [51]. The NaOH alkaline treatment will reduce the lignin and hemi-cellulose, increase the cellulose content of hemp fibers, balance the hydrophilic structure, and provide a better interface bond with PC. As a result, the fiber surfaces will become clean and rough, and the molten polycarbonate will provide better mechanical locking with the fibers [51].

According to Ceylon et al., (2024) [51] to determine the optimum NaOH alkali treatment to be applied to hemp fibres within the scope of the study, 5% and 7% (NaOH/pure water) solutions were applied in four different ways, namely heat treatment (HT) and ambient temperature (AT) [51]. The washed fibres were left to dry overnight at room temperature and then dried at -0.6 bar pressure and 80 ° C for 24 h to remove residual moisture[51]. The samples processed under HT conditions were stirred at 120 °C for 60 min at 200 rpm in a DATHAN SCIENTIFIC MSH-20D device and then washed in tap water for 5 min to remove the solution in the fibers and neutralized [51]. The washed fibers were left to dry overnight at room temperature and then dried at -0.6 bar pressure and 80° C for 24 h to remove residual moisture[51]. The fibers used in the control sample were soaked in pure water for 24 h to remove impurities, and the same drying process was used [51].

According to Ceylon et al., (2024) [51] within the scope of this study, the Anycubic 13 3D printer was chosen to apply the additive manufacturing method [51]. Hemp fibre-reinforced composite samples were prepared as filaments with a 1.00–2.00 mm diameter in the Twin-Screw Extruder device [51]. The composite samples were prepared with 10%, 20%, and 30% fiber ratios, alkali-treated and untreated, and pure PC was used as a control sample[51]. Hemp fibres were cut into 6 mm lengths and prepared as alkali treated and untreated[51]. Alkaline treated fibers were treated in 5% NaOH solution under HT conditions, washed in tap water until the pH was neutral, and left to dry overnight[51]. The untreated fibers were soaked in pure water for 24 h and left to dry overnight at room temperature [51]. The materials were mixed in the twin-screw extruder at a speed of 100 rpm and a temperature of 250^o C [51]. The materials were fed into the extruder via the feed hopper and mixed as a melt at the determined ratios [51]. At first, PC pellets were fed to the extruder barrel and mixed for 2 min, then fibres were fed, and the mixing time was continued for another 1 min [51]. After mixing for 3 min, including the fibre feeding time, filaments with a diameter of 1.0–2.0 mm were obtained [51]. According to Ceylon et al., (2024) [51] composites reinforced with alkali-treated fibers are more homogeneous and less porous than those reinforced with untreated fibers [51]. As the porous structure decreases, the composites become stronger [51-57]. These results are similar to the tensile test results. Alkali treatment provided fullness at the endpoint of the fibers[51]. This fullness increases the stiffness and coincides with the tensile test results[51-57]. Alkali treatment made the fiber surface smoother [51]. This provides a better interface bond with the matrix material. In composites reinforced with alkali-treated fibers, fiber distribution is more homogeneous, and fiber surface breaks and distortions are less common than in untreated composite samples [51-57].

- According to Yemesegen, Eden Binega (2024) [52], this research work amalgamated the rich historical wisdom gleaned from Sub-Saharan African building traditions, particularly the utilization of earthen materials such as cob, bamboo, and hemp, with the rapidly evolving field of 3D printing technology for the development of sustainable and environmentally friendly residential dwellings in tropical and arid regions [52]. This study involves the design of two primary geometric models tailored for 3D printing construction methods, drawing inspiration from historical housing forms in Sub-Saharan Africa [52]. Notably, significant attention is devoted to the integration of earthen materials due to their cost- effectiveness, natural insulation properties, and ecological benefits [52]. The research work by Yemesegen, Eden Binega (2024) [52] explored the incorporation of cob, bamboo, and hemp-based structures into the 3D printing process, acknowledging their eco-efficiency, sustainability, and renewable characteristics [52]. The outcomes demonstrated promising features of these materials, including favorable printability and sustainable characteristics such as potential carbon sequestration for hempcrete[52]. Additionally, the study places emphasis on the revitalization of clay-hemp material as a sustainable building resource[52].

Extensive experimental approaches are employed to investigate mixing ratios, physical properties, deformation characteristics, buildability, and suitability for 3D printing [52]. The research also conducts 3D printing trials to evaluate the material's performance in additive manufacturing [52]. Various 3D printing experiments, including the creation of intricate patterns and mechanical strength tests, provide insights into failure mechanisms and potential mitigation techniques[52]. Moreover, the study highlights into finite element modeling (FEM) and structural analysis considerations for 3D printable clay-hemp structures [52]. The results offer insights into structural behavior and deformation characteristics under different loading conditions, contributing to the advancement of understanding in FEM for additive manufacturing [52]. According to study conducted by Yemesegen, Eden Binega (2024) [52], the integration of sustainable materials with 3D printing technology holds significant promise for advancing the construction industry towards more eco-friendly and efficient practices [52]. This experimental study investigates the feasibility and effectiveness of reinforcing bamboo embedded with hempcrete for 3D printable cobcrete structures as a preliminary study [52]. The experimental setup involves conducting pull-out tests on 3D printed cobcrete specimens to evaluate the bond between bamboo and hempcrete using different reinforcement methods [52]. Finally, conclusions are drawn based on the findings, highlighting the most effective reinforcement techniques and providing recommendations for future research and practical applications in the construction industry[52]. Overall, this study by Yemesegen, Eden Binega (2024) [52], contributes valuable insights into the potential of bamboo reinforced with hempcrete for enhancing the strength and durability of 3D printable cobcrete structures, paving the way for more sustainable construction practices [52].

- Concrete is a popular material for 3D printing, especially in the construction sector. It is composite material of aggregate—usually geological materials such as gravel, sand and crushed rock—that is bonded by fluid cement and hardened over time [58]. In recent years, it has become increasingly easy to use for additive manufacturing. Standard concrete 3D printers are like FDM printers, operating by material extrusion [58]. However, concrete has a huge carbon footprint. According to Statista, manufacturing cement (which is part of concrete) produced 1.6 billion metric tons of carbon dioxide in 2022 alone. Therefore, it is a great news that researchers developed concrete for 3D printing with low carbon emissions [58]. The concrete material for 3D printing that researchers at the Unviersity of Virginia developed has many promising characteristics: It is strong, durable and emits significantly lower carbon emissions than traditional printable concrete mixtures[58].

- The Australian bio-technology company, **Mirreco** continues to be implemented more and more green building solutions and 3D printing in construction [59]. Mirreco is one such company that has worked on finding greener solutions in the building market, basically seeking to build hemp 3D printed houses [59]. The Australian bio-technology company has dedicated itself to a project with a clear vision: Creating a vertically integrated industry going from the farm to finished house, while producing affordable housing and be environmentally responsible in the process [59]. Some of the tools they have taken in use for this project is 3D printing and the use of hemp [59]. Mirreco previously mentioned that hemp in 3D printing filament and the environmental benefits the plant could bring in terms of its overall impact on the environment from growth to production [59]. This is also one of the reasons Mirreco is looking to the plant for their project in combination with 3D technology [59]. Over recent year more and more countries have or are starting to establish hemp crops on an industrial scale [59]. Hemp has historically been used for thousands of year. The crop has a variety of uses, and it has more recently been "re-discovered" in the general market. As mentioned one area the versatile material is being used is 3D printing [59]. Mirreco is contributing to the history by developing their carbon-neutral hemp panels that can be 3D printed into floors, walls and roofs [59]. The company released the concept of their sustainable hemp home designed by the architecture firm Arcforms, based in Perth, Australia back in 2018 [59]. As Hemp itself has the ability to sequester and store carbon dioxide to cut down on greenhouse gasses [59]. It has also been possible to develop hemp-based bio composite materials, that have proven stronger and with improved performances over synthetic materials otherwise used in the industry [59]. Along with the rapid growth cycle of the material of 3 crops per year, there is also an increase in demand on the consumer side for more sustainable solutions [59]. Thus making Mirreco's development of a specialized machine to process an entire hemp plant into separate items, such as seeds, fibers and the hurd, a great tool[59]. Mirreco stated: "The floors, walls and roof will all be made using hemp biomass, and the windows will incorporate cutting-edge technology that allows light to pass through glass where it is converted into electricity [59]. The company's intentions are; to manufacture, sell and/or own and operate a full fleet of mobile machines to process hemp onsite at relevant farming locations[59].
- The building construction with 3D printing technologies could be a game-changer [59, 60]. However 3D printing hemp is difficult at best, as 3D printing pioneer. An Australian, Perth-based company, MIRRECO, are developing a CAST® hemp-based construction 3D printing process that will also be able to store CO_2 removed from the atmosphere [59, 60]. 3D printing processing technologies to provide significant cost reductions and valuable labor/time savings for growers. After harvest, hemp can be processed into different particulate sizes for multiple uses [59, 60]. MIRRECO's strategy is to establish uptake for its processing technologies in the Australian market first, before licensing them world-wide [60]. The combination of hemp particulates and polymers within a unique manufacturing process enables industrial CO_2 to be locked away within these products [59, 60]. Finally, MIRRECO is carrying out R&D charter on other hemp-based innovations such as structural hemp for the construction industry and 3D printing of homes[59, 60]. The company identified 12 particulate variations (which can be produced by MIRRECO's processors) for necessary grades of hemp biomass that form the basis for manufacturing a vast array of hemp products that include 3D printed structures, composites, plastics and other structural building components[59, 60].

In collaboration with the Engineering team at Curtin University, **MIRRECO** are also working on the development of CO_2 storing hemp-polymer composites for structural load-bearing wall panels, under various loading conditions, e.g. uni-axial and eccentric compression, flexible shear and impact loads to satisfy Australian & International standards for residential and light-commercial buildings [59, 60]. A key driving force for MIRRECO is the advancement of the baseline CAST technology from 1st generation non-structural hemp CAST, to 2nd generation structural hemp CAST and then a 3rd generation of hemp CAST 3D printing [59, 60].

- The New York-based company, **Black Buffalo 3D Corp** is one of a small hemp-based construction companies harnessing the power of 3D printing to produce hempcrete in the form of layer-able material, similar to smaller 3D printers, but on a much larger scale [61]. While the U.S. is currently reliant heavily on raw industrial hemp imports from countries like Canada and China, the $500 million fund aims to promote the growth of hemp production in the U.S. for both the domestic and global markets [61]. The national housing shortage continues to deepen as construction efforts move away from small, entry-level homes, and supply chain disruptions drive home prices too high for lower and middle-income families to afford [61]. Additionally, the chronic labor shortage in the construction industry has pushed the adoption of technology-driven solutions into building processes[61]. As an investment opportunities grow, the need for hemp farmers, production managers, engineers, and 3D machine operators to build, repair, and effectively implement these technologies will create new greener jobs [61]. The efficiency of 3D printing outpaces traditional building times and methods. The amount of time to construct a 1,600-square-foot building using the 3D hemp ink model takes around 30 hours compared to the 2-4 months using conventional methods and materials with only a fraction of the physical labor and onsite workforce [61]. However, with hempcrete weighing only an eighth of traditional concrete, cost savings can be realized on packaging, fuel usage, transport logistics, and labor. This company collaboration aims to create an environmentally beneficial solution that serves as an easy and cost-effective alternative to a fossil fuel-invested economy [61]. This solution is aiming to not only be carbon zero, but carbon negative is highly achievable [61]. This is because very little waste is produced, and as hempcrete cures over time, it sequesters CO_2, enabling the buildings to offset the CO_2 produced during the manufacturing and construction processes and additional emissions produced by non-green industrial activities[9, 61]. Black Buffalo's hemp-based building material is an efficient insulator and is both waterproof and fireproof, making it an ideal solution for communities impacted by the effects of climate change, such as California and Australia, where wildfires are a yearly occurrence, and Texas, where the rate of flash flooding is high [61]. Extreme weather events like these are only expected to intensify, and solutions like this can ensure climate change resilience and savings on both building and natural disaster insurance costs [61].

- Cannabis has been a hot topic of debate in recent years, with discussions ranging from its medical uses to its environmental benefits and sustainable capabilities [1-41, 62]. In recent years, there has been a renewed interest in hemp as a versatile and environmentally friendly material [1-41, 62]. Hemp's ability to reduce water consumption, pesticide use, and its overall positive environmental impact make it a promising solution to many ecological challenges[1-41, 62]. One of the lesser-known yet promising applications of cannabis is in the form of hemp 3D printer filament [1-41-62]. As the world of 3D printing continues to evolve, hemp filament is emerging as a viable and eco-friendly alternative [51- 62]. One of the biotechnology company **Makeinica** at **Bengaluru, Karnataka**, India has developed manufacturing process, and practical applications of hemp filament in 3D printing, with a focus on its potential for 3D printing services in India [62]. Hemp is a highly versatile plant that can be used for a wide range of applications, including bio-fuel, textiles, and now, 3D printer filament [1-62]. The development of hemp filament brings a new dimension to the additive manufacturing industry, offering an eco-friendly alternative to traditional plastic filaments [62]. According to Makeinica at Bengaluru, Karnataka, India, 3D printing is revolutionizing manufacturing by reducing waste, speeding up processes, and often using less energy [62]. However, achieving a completely closed-loop system with environmentally friendly filaments remains a challenge [51- 62]. Hemp filament, combined with biodegradable materials like PLA (polylactic acid) offers a sustainable solution for 3D printing service in India [62]. The process of making hemp filament is relatively straightforward [62]. Typically, PLA is used as a polymer base, and hemp fibres are ground into fine particles and mixed into the PLA. This hybrid material retains the biodegradable properties of PLA while adding the unique benefits of hemp [62]. The resulting filament often has a natural texture and color, enhancing its eco-friendly appeal. Several companies have developed their versions of hemp 3D printer filament, contributing to the growing market for biodegradable and sustainable materials [62]. **D4MAKER** is one such company that has developed biodegradable plastics, including hemp filament, which can be recycled or composted after use. Another company, **3Dfuel** has released a series of eco-friendly composite materials in partnership with c2renew. Their product line includes Wound Up (coffee filament), Buzzed (beer filament), Landfillament (trash filament), and Entwined (hemp filament) [62]. These materials are made using waste products and Ingeo PLA, providing functional and sustainable 3D print online. Furthermore, Kanèsis is an Italian company committed to natural materials designed for the manufacturing industry[62]. Hemp filament shares many printing properties with PLA, making it easy to use for various 3D printing applications [62]. It can print at lower temperatures than PLA, is odorless, and has low warp, eliminating the need for a heated bed. Optimal bed temperature, if used, is around 45^{o}C [62]. Due to its ease of use and biodegradable attributes, hemp filament is ideal for daily prototyping and experimental projects. It also offers a unique texture and appearance, making it suitable for specific aesthetic applications [62]. Gardening is a popular hobby that allows people to connect with nature and express their creativity. 3D printing with hemp filament can enhance gardening by providing cost-effective and eco-friendly tools and accessories. **3Dfuel** is a company that has made significant strides in the development and commercialization of eco-friendly 3D printing materials[62]. They have partnered with **c2renew** to produce a series of sustainable filaments, including their popular hemp-based filament. **3Dfuel's** Entwined filament has been used by various companies and educational institutions to create sustainable and functional 3D printed objects[62]. One notable example is the collaboration with the University of Minnesota, USA where students and researchers have used **Entwined** to prototype and produce eco-friendly products[62]. The University of Minnesota, USA design and engineering departments have utilized the filament for projects ranging from sustainable packaging solutions to biodegradable consumer goods [62]. The use of Entwined filament has helped the University of Minnesota to reduce its environmental footprint while promoting sustainability in design and engineering education. The success of this collaboration has also led to increased interest in hemp filament among other educational institutions and industries [62]. **Kanèsis** is an Italian company dedicated to developing natural materials for the manufacturing industry[62]. They have created HempBioPlastic (HBP), a filament made from hemp fibers, which is designed to reduce environmental impact and provide sustainable solutions [62]. **Kanèsis** has partnered with several Italian design and manufacturing companies to incorporate HBP filament into their production processes[62]. One such collaboration is with the furniture design company, **Riva 1920**[62]. Riva 1920 has used HBP filament to create eco-friendly furniture components, including decorative elements and functional parts [62]. The use of HBP filament has allowed Riva 1920 to offer sustainable furniture options to their customers, aligning with their commitment to environmental responsibility [62]. This partnership has also showcased the potential of hemp filament in high-end design and manufacturing, encouraging other companies to explore similar sustainable materials. **3D Brooklyn** is a New York-based company that focuses on creating sustainable 3D printing solutions[62]. They have developed a range of eco-friendly filaments, including a hemp-based filament, which they used to produce a variety of products. 3D Brooklyn has collaborated with the fashion brand, Zady, to create sustainable fashion accessories using hemp filament. Zady, known for its commitment to ethical and sustainable fashion, has used 3D Brooklyn's hemp filament to produce items such as buttons, buckles, and other garment components [62]. This collaboration has enabled Zady to offer fully sustainable fashion products, from the materials used to the final production process [62]. The success of this partnership has highlighted the versatility of hemp filament in the fashion industry and has inspired other fashion brands to consider sustainable 3D printing solutions. **Filamentive** is a UK-based company that specializes in producing sustainable 3D printing filaments[62]. They have developed a range of eco-friendly materials, including a hemp-based filament, which is designed to reduce the environmental impact of 3D printing services [62]. Filamentive's hemp filament has been adopted by the design and architecture firm, Foster + Partners. The firm has used the filament to create sustainable architectural models and prototypes. The use of hemp filament has allowed Foster + Partners to demonstrate their commitment to environmental responsibility while showcasing the potential of sustainable materials in architecture and design [62]. This success story has encouraged other design and architecture firms to explore the use of eco-friendly 3D printing materials. TreeD Filaments is an Italian company that produces a variety of 3D printing filaments, including a hemp-based filament known as HempBioPlastic (HBP) [62]. They focus on creating sustainable and high-quality materials for the 3D printing industry. **TreeD** Filaments has partnered with the automotive company, Fiat, to explore the use of hemp filament in the production of car components. Fiat has used HBP filament to prototype and produce interior parts, such as dashboard elements and trim pieces [62]. The collaboration with Fiat has demonstrated the potential of hemp filament in the automotive industry, offering a sustainable alternative to traditional plastic materials [62]. This success story has paved the way for further research and development of eco-friendly materials in the automotive sector[62].

- **MatterHackers** is a leading retailer of 3D printing materials and equipment. They offer a wide range of filaments, including a hemp-based filament that has gained popularity among their customers[62]. MatterHackers has worked with the non-profit organization, Precious Plastic, to promote the use of hemp filament in community recycling projects. Precious Plastic has used the filament to create recycled products, such as containers and tools, which are distributed to communities in need [62]. The use of hemp filament in these projects has helped Precious Plastic promote sustainability and environmental awareness in communities around the world [62]. This collaboration has highlighted the potential of hemp filament in social and environmental initiatives, encouraging more organizations to adopt sustainable 3D printing materials [62]. Hemp filament is a promising and sustainable alternative to traditional 3D printing materials [62]. Its eco-friendly properties, ease of use, and unique texture make it an excellent choice for various applications [62].
- As legislation continues to evolve and more companies develop hemp-based products, the potential for hemp filament in 3D printing at Bangalore, Karnataka, India will only grow[1-62]. Hemp is an environmental enthusiast, hemp filament offers a versatile and sustainable option for your 3D printing needs [1-62]. Makenica HQ SLA | FDM | SLS | MJF | Vaccum casting 46, 7th Main Rd, JC Industrial Estate, Yelachenahalli, Kumaraswamy Layout, Bengaluru- 560062, Karnataka India. Phone + (91) 96067-70777 (www.makenica.com). Another address: Makenica Unit II-ISRO Layout, 1974, 8th Main, Stage II, KS Layout, Bengaluru- 560078, Karnataka, India. (support@makenica.com) [62].
- One of the research work has aimed at investigating the feasibility of implementing natural fibres, such as hemp fibers, in lieu of synthetic fibers as sustainable and environmentally friendly resources in concrete production [63]. In the first stage of this study, a surface treatment was applied to hemp fibers 12 mm± 2 mm in length using a 5 wt% sodium hydroxide (NaOH) solution to determine the effect treated hemp fibers have on cementitious composites [63]. Additionally, three cement mortars were made with different fiber ratios (0.75%, 1.5%, 3%) to determine the optimal hemp fiber content of the mortars [63]. Concrete samples were cast also concrete filaments were printed using the custom-made 3D concrete printer [63]. Form cast samples

and printed filament samples were produced to determine the compressive, tensile, and flexural strengths as well as the shrinkage capacity, rheological properties, structural build up, extrudability, buildability, and fiber dispersion of the mortars[63].

- Concrete, is not a very environmentally-friendly material. It comes with a lot of carbon emissions and that is a big issue [64]. The 3D printing construction which is a more environmentally-friendly process for two reasons 1) do not need to place to concrete anywhere else but at the locations where need it, and 2) do not need formwork, which would usually use just a few times and then throw it away [64]. So these are two major benefits of the process itself [64]. Hempcrete is a sustainable material[1-64]. Hemp by itself is a very attractive material in construction because it, essentially, has a negative carbon footprint – it sequesters a lot of CO_2[1-64]. The second challenge is for the team to design structures that are structurally code compliant and also code compliant in terms of energy performance[1-64].
- **Black Buffalo 3D Corp**. plans to use hemp fiber in the cement-based mix it uses to 3D-print buildings [65]. Pennsylvania's hemp supply chain is taking a major step as a next-generation construction company sets up research and manufacturing operations in Monroe County [65]. The company will assemble the industrial-scale printers, develop products and train customers in Smithfield Township, just outside East Stroudsburg [65]. Black Buffalo sells 3D construction printers and produces a proprietary mix, called the ink, that the printer processes into the desired form [65]. Black Buffalo's ink is stronger than concrete and used for the structural parts of the building, such as the walls [65]. Hemp would replace a material in the mix that is less environmentally friendly to produce[1-65]. 3D-printing a building takes big equipment [65]. The printer that Black Buffalo is selling now produces forms up to 27 feet high, which is two or three stories [65]. The base model can print nearly 700 square feet but can be extended to more than double[65]. The printer is built on a rail system, so it could produce a set of row homes simply by moving down one set of tracks [65]. The company recently held its first public exhibition at a builders show in Orlando, USA printing a tiny house[65]. And while many large-format 3D printers have to stop after a half dozen layers to let the ink cure, Black Buffalo's ink is designed so that the machine can run continuously [65]. The loop just has to be about two minutes long/ lack. Buffalo has run its printer as long as 16 hours straight. At its current rate, the machine could produce the outer and inner walls of a 1,600-square-foot building in 30 hours [65]. The machine only pumps out excess ink at the beginning of a print — when the consistency is being checked — and at the end of the job [65]. Black Buffalo has determined how much excess will be produced, so that material can be used for things other than load-bearing walls. Black Buffalo's investment in the hemp supply chain is one of the largest in Pennsylvania to date [65]. The company will invest $36 million in the project and create 71 jobs within three years, according to the Department of Community and Economic Development, USA [65]. The agency has offered Black Buffalo a $2.4 million loan and $426,000 in grants as incentives for the expansion. Black Buffalo, which has an existing facility in Elizabeth, New Jersey, is part of Big Sun Holdings, whose majority shareholder comes from the South Korean family that founded the Hyundai automotive company [65]. Black Buffalo and Hyundai are not affiliated. Black Buffalo's complex near East Stroudsburg could become a sort of hemp business park. In addition to having a 150,000-square-foot manufacturing plant and training center, and hosting the Hemp Innovations Foundation's research work, Black Buffalo plans to collaborate with local schools and even 3D-print affordable housing at the site [65]. The company will also need farmers producing hemp fiber [65]. For its initial experimentation with the crop, Black Buffalo will require hemp with specific qualities to maintain structural integrity and ensure that the ink flows properly through the 3D printer. The 3D-printing construction industry is still young, but it could be big [65]. After working hemp into the existing printing material, the company wants to develop an ink with a lime-based binder[65]. Lime absorbs carbon dioxide as it cures, so the ink will trap the greenhouse gas coming out of the hemp fiber instead of releasing it into atmosphere [65]. The 3D printing will increase efficiency across the construction industry, not just in home building [65]. Companies could cut their transportation costs by producing massive forms for tunnels and bridges on site, rather than hauling them from distant factories. "Every major construction site should have a 3D printer [65].
- Australian hemp company **Mirreco** is creating a 3D printing procedure that utilizes hemp biomass as a material for the fabrication of building panels for houses [66]. The company specializes in machines that can process an entire hemp plant and separate it into various items [66]. As a result, the company can offer a sustainable and biodegradable material option for housing. The hemp-based process has drawn the interest of Arcforms, who want to help showcase the potential for hemp biomass within the construction sector [66]. In a released statement, the company made clear its reasons for using hemp, citing its unique properties[66]. When compared with traditional building materials, Mirreco claims the 3D printed hemp-based panels are structurally seem, simple to produce and supply superior thermal performance. It is also useful for floors, roofs and interiors, so it is utility does not just stop at paneling [66].

The 3D printing industry is no stranger to hemp-based products [66]. Filaments based on it have been available for quite a while now [66]. This has, no doubt, something to do with the worldwide lifting of restrictions on hemp and related products [66]. The proliferation of hemp and its derivatives has led to widespread interest in hemp paper and hempcrete, a type of concrete [66]. While Mirreco provides the processing machinery, Arcforms will design the houses [66]. The house looks aesthetically pleasing and functional, although it is just a simulation for now [66]. "The floors, walls and roof will all be made using hemp biomass, and the windows will incorporate cutting-edge technology that allows light to pass through glass where it is converted into electricity [66].

- The construction method of 3D printing reduces the use of wooden formwork, and this can help to reduce or eradicate deforestation. However, the use of concrete still has an adverse effect on the environment due to its carbon footprint [67]. The use of clay and earthen materials for 3D printing has recently gained attention due to its low environmental impact in comparison to concrete. 3D printing of earthen-based materials consists of using rice husk, chopped straw, clay, cob mixture, and sand [67]. Earthen materials are considered as one of the oldest materials in home building on the planet. Earth-based building materials are eco-efficient, sustainable, renewable, recyclable, and carbon-zero or even carbon-negative materials for the case of hempcrete [1-67]. Cob, hempcrete, and bamboo-based materials are environmentally low impact and eco-friendly building materials [67]. With the current high demand of using earthen materials with the interest of modernizing the material mix, construction methodology, and geometry usability, relevant theoretical and experimental studies are necessary [67]. Earthen building materials are used together with bamboo to enhance the strength of the structures [67]. Bamboo has been used for centuries as a central pole or frame of the house to support the structure and the walls[67]. The use of green materials in construction is becoming highly desirable since it helps to reduce the environmental impact during construction. Not only the use of material, but also the method of construction highly impacts the sustainability of home building [67]. The construction method of 3D printing reduces the use of wooden formwork, and this can help to reduce or eradicate deforestation [67]. The use of clay and earthen materials for 3D printing has recently gained attention due to its low environmental impact in comparison to concrete [67]. With the current high demand of using earthen materials with the interest of modernizing the material mix, construction methodology, and geometry usability, relevant theoretical and experimental studies are necessary [67].
- 3D Printing hempcrete will allow more precise distribution of materials, and can naturally be combined with various topology optimisation techniques to further reduce material usage while maintaining strength, which is required for resilient housing [50- 68]. Hemp has historically been used for a wide range of applications spanning from rope production and textile manufacture, through to more modern day applications such as its usage in hemp-based plastics [1-68]. Hemp fibers are very strong, and they are also very cheap. It has also been used as a construction material named hempcrete for quite some time (thousands of years in fact)[68]. The researchers, funded by a $3.74 million grant from the Department of Energy, are now planning to 3D print buildings with millenia-old building material[68]. Hempcrete consists of hemp particulate, lime and sand. The project is funded under the HESTIA program which aims to increase the total amount of carbon stored in buildings to create carbon sinks, which absorb more carbon from the atmosphere than released during construction[68]. **HESTIA** stands for "Harnessing Emissions into Structures Taking Inputs from the Atmosphere". Material-wise, hempcrete is a breathable porous material with excellent fire resistance and thermal insulation properties, the latter being beneficial in reducing heating and cooling energy demands [68]. It is significantly lighter than concrete, and a fraction of the compressive strength, so it requires supports to carry vertical loads [68]. In terms of other ecological benefits, production and use of hempcrete has a net carbon-negative environmental effect. This is in opposition to the manufacture of traditional cement which is incredibly energy intensive and pretty bad for CO_2 emissions [68].

Cement is the source of about 8% of the world's carbon dioxide emissions, to put that into perspective. Hempcrete is carbon negative because plants absorb CO_2 from the atmosphere while growing, so the hemp acts as a carbon sink before the plants are even harvested [68]. The CO_2 will remain locked inside the block, and indeed the block will absorb even more carbon through its life [68]. The buildings have been designed with modern design codes in mind making it more likely to be adopted by the construction industry[68]. While there have been some forms of hempcrete around for eons, modern hempcrete building processes are either cast or spray forming directly on the construction site, or assembling constructions of pre-cut hempcrete blocks, manufactured off site[68].

- Texas A&M will develop novel resilient net-carbon-negative building designs for residential and potentially commercial applications via large-scale 3D printing using hempcrete, a lightweight material made of the hemp plant's woody core mixed with a lime-based binder [68, 69]. The team will devise (1) printable, sustainable, and durable hempcrete mix designs, (2) code-compliant building designs in terms of structural and energy performance, and (3) a novel, risk-based building-level life cycle analysis that will account for environmental impacts under service conditions and from hazard-induced damages (e.g., hurricanes, earthquakes) [69]. The team will further develop digital plans and building information models for selected net carbon negative building designs that can be fed directly to construction printers and provide design methodologies per existing design codes[69]. HESTIA technologies will reduce the carbon footprint of the built environment. Building materials and designs developed under HESTIA will draw down and store CO_2 from the atmosphere[69]. A variety of promising carbon storing materials are being explored and commercialized for building construction. Currently these materials are generally scarcer, cost more per unit, and/or face performance challenges (e.g., flame resistance for biogenic carbon-containing materials) [69] . HESTIA seeks technologies that overcome these barriers while nullifying associated emissions and increasing the total amount of carbon stored in the finished product [69].

- Hempcrete is made by mixing hemp powder, fibres or shives with lime and water, creating a lightweight, green building material[1-70]. The production of conventional construction materials such as concrete requires large amounts of energy and releases large amounts of CO_2 (carbon dioxide). Therefore, hempcrete is a net carbon-negative material, which can provide major environmental benefits [70]. Sustainability will be further promoted by designing hempcrete structures more resilient to natural hazards than commonly used lightweight wood frame construction [70]. Resilience to natural hazards is intertwined with environmental sustainability because building damage and subsequent repairs due to extreme events such as hurricanes resulted in a major environmental impacts[1-70]. Hempcrete has already been used globally in residential construction and prefabricated modular construction [1-70]. Hempcrete has excellent fire resistance and thermal insulating properties that can reduce heating and cooling energy demands [70]. It is water-resistant and offers good acoustic properties. As part of the project, building designs will be printable and created to achieve structural and energy performance that will comply with modern design codes. Further digital designs of printable hempcrete buildings will facilitate adoption by the construction industry [70]. The advancements of this project will contribute to the U.S. maintaining its worldwide in advanced construction methods and infrastructure sustainability and resilient technologies [70]. A plan from Texas A&M University researchers to 3D print new resilient buildings using hempcrete has the potential to lower the environmental impact of traditional construction methods and make housing more affordable and available[70].The project will be funded by a $3.74 million grant from the U.S. Department of Energy Advanced Research Projects Agency-Energy (ARPA-E) Harnessing Emissions into Structures Taking Inputs from the Atmosphere (HESTIA) program[70]. Dr. Petros Sideris, Assistant professor in the Zachry Department of Civil and Environmental Engineering, will lead the project as principal investigator to develop residential and potential commercial construction designs. His team consists of assistant professor Dr. Maria Koliou, department head and professor Dr. Zachary Grasley, and professor Dr. Anand Puppala from the department, and associate professor Dr. Manish Dixit and professor Dr. Wei Yan from the Texas A&M College of Architecture[70].
- Hempcrete is a bio-based self-bearing envelope, thermal insulation building material that is becoming more popular and has a low environmental impact, especially CO_2 emissions [9, 44-73, 74]. One of the study by Sinka et al., (2022) [73] reported solutions for hempcrete printing using a custom-built type 3D printer typically used for concrete 3D printing [73]. Preliminary research showed that hempcrete can be printed at a relatively low density of 660 kg/m3 and achieved an adequate buildability and compressive strength for printing individual wall elements [73, 74]. Therefore, high-density hempcrete should be printed as an outer wall shell (similar to Contour Crafting) and the middle layer is filled with lower density thermal insulation hempcrete [73]. Hence, such material could reduce the negative environmental impact of the construction industry while improving its productivity through 3D printing[73]. According to the study conducted by Sinka et al., (2022) [73], five main conclusions can be drawn from the results: 1) Hempcrete is a 3D printable at a density of 660 kg/m3, has sufficient buildability and strength to form an outer shell layer for self-supporting walls, the inner layer of which can be filled with less dense hempcrete with a density of 220 kg/m3, providing adequate thermal resistance at an overall wall thickness of 400–640 mm [73]. 2) Such walls have a significantly lower environmental impact as they can store from 1.21 to 16.7 kg of CO_2 eq. per m^2, in contrast to the walls of traditionally used materials, which emit up to 147 kg of CO_2 eq. per m^2[73]. 3) The fresh binder properties of the 3D printed samples are similar to the properties of the cast samples, thus facilitating their testing and preliminary development of new formulations without printing [73]. 4) The mechanical strength properties of the 3D printed samples are lower than the properties of the cast samples, by 31 % in compressive and 67 % in flexural strength due to outer carbonation layer and specimen preparation using sawing. To overcome this problem in the future studies, samples will be printed in special moulds [73]. The use of hempcrete material in combination with 3D printing opens up a wider range of uses for this material and the possibility of eliminating the negative impact of the construction industry on the environment [73]. This study did not consider the optimization of printable forms to reduce material consumption, which would have an additional positive effect compared to traditionally used building materials but will be tested in future studies[73].
- According to Zachary et al., (2024) [75], there is a growing interest in utilizing sustainable and environmentally friendly resources in construction materials to promote long-term viability and resilience of construction industry [75]. This research was aimed at investigating the feasibility of implementing natural fibres, such as

hemp fibers, in lieu of synthetic fibers as sustainable and environmentally friendly resources in concrete production. In the first stage of this study, a surface treatment was applied to hemp fibres 12 mm ± 2 mm in length using a 5 wt.% sodium hydroxide (NaOH) solution to determine the effect of treated hemp fibers on cementitious composites [75]. Additionally, three cement mortars were made with no fibres, untreated fibres, and treated fibres to determine the effect of fibre treatment on the mortars. In this study, concrete samples were cast and concrete filaments were printed using the custom-made 3D concrete printer [75]. Form cast samples and fresh concrete samples were produced to determine the compressive, tensile, and flexural strengths as well as the fibre dispersion and rheological properties of the mortars [75]. This study also concluded that future research is required to investigate the structural build up, extrudability, buildability, and shrinkage capacity of HFR3DPC [75]. Utilizing hemp fibre as reinforcement in 3DPC has the potential to offer a sustainable concrete mixture that could not only assist in offsetting the carbon emissions associated with cement production but could also continue to sequester CO_2 and act as a carbon storage bank throughout the duration of the structure's life[75]. The literature shows that the cultivation of hemp offers phytoremediation benefits that could help to restore distressed crop land and reduce the need for harmful chemical herbicides and pesticides [75]. In this study, hemp fibres did not have a positive influence on the mechanical properties of the hardened cement but did improve the deflection of the flexural beam samples [75]. The increase of yield stress recorded during the green strength test showed that the hemp fibres have the potential to increase the buildability of 3D printable cementitious composites [75].

- Hempcrete has not only a help in protecting the environment, global warming and climate change. Hempcrete also provides comfort in the structures [44- 75]. Its hygrometric behaviour leads to indoor air quality and a relaxed indoor microclimate condition. It displays low thermal conductivity, low density, low strength, high absorptivity and high moisture buffer capacity. It is ensuring a building envelope, which can be used in the wall, roof and floor [44- 75]. The mixture proportions should be calculated properly according to the application area, so as to evade unforeseen effects. It is an appropriate plant for growing in environments other than extreme desert climates and high mountain regions [44- 75].
- **Tvasta**, **Chennai**, Tamil Nadu, India is a first principles-based technology builder, will use the power of Automation and Robotics to build 3D Printing Platforms that enable the building of infrastructure and manufactured components faster, cheaper and in a more sustainable manner [127, 128-130]. Tvasta will develop category-creating platform technologies that disrupt the Construction Industry by automating 80% of construction while building distributed Infrastructure solutions and mass[127, 128-130]. Tvasta will develop 3D printing by creating specific technological platforms that can be used for applications across the Manufacturing sector for producing mass customized end components with high precision[127, 128-130]. Tvasta, Bala Complex, Old No.345, New, 172, Rajiv Gandhi Salai, OMR, Sholinganallur, Chennai, Tamil Nadu 600119 [127, 128-130]. The process of building a 3D-printed Tvasta house is not just different but a lot quicker than conventional construction [127, 128-130]. It is built with focus on reduced build-time, zero-waste construction and optimised production. To start with, the structure was printed using a special concrete mix through which large-scale 3D structures were made[44- 127, 128-130]. The concrete mix is a base of ordinary cement which has a lower water-cement ratio. While concrete is the primary material for typical construction projects as well, the energy consumed to mix and transport it is way more than in 3D printing [44- 127, 128-130].
- The concept of a 3D printed house is rapidly transforming the construction industry [127, 128]. With the potential to reduce costs, minimize waste, and significantly speed up the building process, this technology has caught the attention of innovators, architects, and environmentalists alike [44- 130]. In India, where housing demand is rising due to urbanization, 3D printed homes are emerging as a sustainable and efficient solution [127, 128-130]. A 3D printed house is a building structure created using additive manufacturing technology [127,128-130]. Instead of traditional construction methods, which rely on bricklaying or concrete pouring, 3D printing uses specialized machines to deposit material layer by layer [44- 130]. These machines, guided by digital designs, can produce complex and precise structures with minimal human intervention. In Bengaluru, Karnataka, India, the techniques of 3D printed homes is used for the construction of expensive, Villas and apartments [44- 130].
- **India** has started exploring the potential of 3D printed homes, particularly in addressing housing shortages and disaster relief needs [127-130]. Some notable milestones include: **India's First 3D Printed House**: India's first 3D printed house, developed by **Tvasta** Manufacturing Solutions in collaboration with IIT Madras, marked a groundbreaking achievement in sustainable construction [127, 128]. Completed in 2021, this single-story structure spans 600 square feet and was built in just five days using an eco-friendly concrete mixture [127, 128]. Designed to address India's affordable housing needs, the house demonstrates the potential of 3D printing to create durable, cost-effective homes while reducing construction time and material waste [127, 128]. This pioneering project showcases India's stride towards innovative and sustainable building technologies [127, 128]. Affordable Housing: Organizations like Habitat for Humanity are piloting projects in India to provide low-

cost 3D printed homes to underserved communities [127, 128]. Disaster Relief Housing: Quick assembly and portability make 3D printed homes ideal for regions affected by natural disasters like floods and earthquakes [127-130].

- Benefits of 3D Printed Houses 1. Cost Efficiency: Construction costs are significantly reduced due to minimal labor and material wastage. 2. Time Savings: Entire homes can be built within days, compared to months using traditional methods. 3. Sustainability: Materials used are often recyclable, and the process generates less waste. 4. Customization: Complex and unique designs can be executed with precision. Reduced Dependency on Skilled Labor: Automation minimizes the need for a large, skilled workforce. ome of the advantages of concrete 3D printing include: Reduction of carbon footprints through the use of eco-friendly raw materials [127-130]. Creation of sustainable and green buildings by utilizing industrial waste and recycled materials. Cost savings of approximately 30% compared to traditional construction methods[127-130]. Elimination of lead time for manufacturing, resulting in faster construction. Construction of high-quality buildings with a lifespan exceeding 50 years [127-130].
- **3D printed post office at Bengaluru, Karnataka**, India: In another first, construction of India's first 3D - printed post office is complete at the Cambridge Layout in the Halasuru area, Bengaluru, Karnataka, India [127-130]. The post office is a three-storied 1000 sqft 3D-printed building[127-130]. Larsen & Toubro, the only company that is undertaking 3D enabled construction in India and constructed this project in collaboration with IIT Madras [127-130]. Houses that are designed and built using construction technologies that use the 3D printing method are known as 3D printed homes[127-130]. 3D printed homes are faster to build and are superior to the traditionally constructed structures in many ways [127-130]. Created by Tvasta Manufacturing Solutions, a start-up founded by the alumni of IIT-Madras, Tamil Nadu, India, this 3D-printed house overcomes the pitfalls of conventional construction. The house was inaugurated by finance minister Nirmala Sitharaman, via videoconferencing [127-130].
- According to the World Economic Forum, by 2030, three billion people will need improved housing. That means building 96,000 new homes every day. 3D printing technology can create high-quality homes in a fraction of the time and cost of traditional construction [127-130]. Tvasta's 3D home was built in just five days [127-130]. Hence, 3D construction technology can produce houses cheaper and faster than traditional building techniques. The method has already provided homes for people around the world. If adopted at a large scale, this approach could put roofs over millions of people's heads[127-130].
- Disadvantages of concrete 3D printing: This innovative construction technique also has a few disadvantages, including: High power consumption, resulting in significant environmental impacts compared to conventional methods [127-130]. Expensive cost of 3D printers. Limited availability of materials used in 3D printing [127-130]. Slow process for mass customization [127-130]. Use of harmful chemicals like styrene and caprolactam, leading to emission of ultrafine materials that can potentially enter the bloodstream. Generation of excessive plastic by-products. Lack of user-friendliness [127-130].

10. Conclusion

Industrial *Cannabis sativa* (hemp or fiber type) has many applications particularly to produce paper, ropes, food, medicines, cosmetics, hempcrete, leather, bioplastic, biochar, 3D printing homes and textiles. Hemp fibers are used to create durable and eco-friendly fabrics for clothing, upholstery, and accessories. Now a days, there is a growing interest in utilizing sustainable and environmentally friendly resources in construction materials to promote long-term viability and resilience of construction industry. Polymers reinforced with natural fibers are becoming more popular in 3D printing due to the numerous advantages they offer such as altering the mechanical properties of the polymer. In fact, natural fiber-based composites are more recyclable than those reinforced with glass or carbon fibers. Utilizing hemp fiber as reinforcement in 3D printing has the potential to offer a sustainable concrete mixture that could not only assist in offsetting the carbon emissions associated with cement production but could also continue to sequester CO_2 and act as a carbon storage bank throughout the duration of the structure's life. The use of hempcrete material in combination with 3D printing opens up a wider range of uses for this material and the possibility of eliminating the negative impact of the construction industry on the environment. The hemp-based construction companies harnessing the power of 3D printing to produce hempcrete in the form of layer-able material, similar to smaller 3D printers, but on a much larger scale. Hempcrete has excellent fire resistance and thermal insulating properties that can reduce heating and cooling energy demands. It is water-resistant and offers good acoustic properties. Therefore, building designs will be printable and created to achieve structural and energy performance that will comply with modern design codes.

Hemp can be transformed in filament to be used for 3D printing. Biodegradable, recyclable and free from toxins, it can replace petroleum-based plastics. The material has a higher impact resistance than regular PLA. Bioplastic made using hemp is fully biodegradable and compostable. 3D printing at Makenica in Bengaluru, Karnataka, India is revolutionizing manufacturing by reducing waste, speeding up processes, and often using less energy. However, achieving a completely closed-loop system with environmentally friendly filaments remains a challenge. Hemp filament, combined with biodegradable materials like PLA (polylactic acid), offers a sustainable solution for 3D printing service in India.

The production of conventional construction materials such as concrete requires large amounts of energy and releases large amounts of CO_2 (carbon dioxide). Therefore, hempcrete is a net carbon-negative material, which can provide major environmental benefits. Hempcrete is carbon negative because plants absorb CO_2 from the atmosphere while growing, so the hemp acts as a carbon sink before the plants are even harvested. That CO_2 will remain locked inside the block, and indeed the block will absorb even more carbon through its life. 3D Printing hempcrete will allow more precise distribution of materials, and can naturally be combined with various topology optimization techniques to further reduce material usage while maintaining strength, which is required for resilient housing. There are many studies reported that 3D printing filaments were produced from hemp hurd fibre-reinforced polylactide (PLA) composites. An Australian, Perth-based company, MIRRECO, are developing a CAST® hemp-based construction 3D printing process that will also be able to store CO_2 removed from the atmosphere. The house looks aesthetically pleasing and functional, although it is just a simulation. The floors, walls and roof will all be made using hemp biomass, and the windows will incorporate 3D printing-cutting-edge technology that allows light to pass through glass where it is converted into electricity. The efficiency of 3D printing outpaces traditional building times and methods. The use of green materials in construction is becoming highly desirable since it helps to reduce the environmental impact during construction and use phases. Not only the use of material, but also the method of construction highly impacts the sustainability of home building. The integration of sustainable materials such as hempcrete with 3D printing technology holds significant promise for advancing the construction industry towards more eco-friendly and efficient practices

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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