

Environmental Impact of Polymer Fiber Manufacture

Manul Amarakoon, Hussain Alenezi, Shervanthi Homer-Vanniasinkam, and Mohan Edirisinghe*

This review focuses on the effects on the environment due to the production of polymer-solvent solutions and the manufacture of polymeric fibers of thicknesses from a nanometer up to a millimeter using these solutions. The most common polymeric fiber manufacture methods are reviewed based on their effects on the environment, particularly from the use of hazardous materials and energy consumption. Published literature is utilized to analyze and quantify energy consumption of the manufacturing methods electrospinning, phase separation, self-assembly, template synthesis, drawing and pressurized gyration. The results show that during the manufacturing stage of the lifecycle of polymeric fibers, pressurized gyration is more environmentally efficient primarily due to its mass-producing features and fast processing of polymeric solutions into fibers, it also works best with water-based solutions. Further green alternatives are described such as the use of sustainable polymers and solvents to enhance the environmental benefit. Overall, it is shown that the most effective method of curbing the environmental impact of manufacturing polymeric fibers is the use of nontoxic, water-soluble polymers along with the evasion of toxic solvents.

chemical modification. There are mainly semicrystalline polymers that are extruded and drawn in a diverse range of cross-sectional configurations.^[2] More recently, the use of submicrometer synthetic polymeric fibers in medical applications such as tissue engineering and wound dressings has also been extensively researched.^[3] The versatility in manufacture and production processes, along with their broad range of material properties, significantly contributes to the increasing use of polymers. It is abstruse to visualize our everyday lives without polymers or plastics.

Plastics use polymers as their main ingredient. However, the application of plastics has serious drawbacks with regard to the negative environmental effects. There are many research articles and scholarly forums on the environmental impact of plastics and polymers, which is the production output. However, the environmental impact of the extraction of materials for polymers and solvents and the

manufacturing processes of the final polymeric fibers is less discussed.

Plastic mediums commonly require hundreds of years to disintegrate in the natural environment.^[4] At present, the world has shown many environmental issues mainly due to landfill and plastic pollution. Plastic pollution from a catastrophic disaster in 2021 resulted in 70–75 billion individual plastic pellets from the sinking X-Press Pearl ship flooding over 300 km of Sri Lanka's coast.^[5,6] **Figure 1** shows the aftermath of the disaster, which resulted in the countless loss of rare endangered marine species, such as rare turtles. These pellets are similar to those used in polymeric fiber manufacture methods such as electrospinning and pressurized gyration, thus it is useful to review and assess the environmental impact of manufacturing from these processes.

There has been a strong focus on the advancement of the use and manufacture of biodegradable polymers due to their ability to easily decompose in the natural environment, which is significantly less harmful to the environment.^[7] The manufacture process of biodegradable plastics is similar to regular plastics, apart from the materials utilized. However, the use of biodegradable polymers is not sufficient to curb the environmental impact of polymer usage, as they have some drawbacks. For instance, biodegradable polymers such as polyvinyl alcohol (PVOH/PVA), and polycaprolactone (PCL) are made from petrochemicals that play a significant role in global warming.^[8] Thermoplastics are recyclable unlike thermosets, where polymeric fibers are mainly

1. Introduction

Polymers are long repeating chains of molecules with distinctive material properties, determined by the type of molecules and their bonding. Polymers are utilized in almost every aspect of modern human life. For instance, in the making of kitchen utensils, wearables, vehicle components, and furniture, which are a fraction of its applications. Synthetic polymeric fibers such as nylon and polypropylene possess advantageous physical features. For instance, they improve mechanical properties and provide high specific surface area.^[1] Synthetic fibers are people-made fibers primarily derived from petroleum derivatives via

M. Amarakoon, H. Alenezi, S. Homer-Vanniasinkam, M. Edirisinghe
 Department of Mechanical Engineering
 University College London
 Torrington Place, London WC1E 7JE, UK
 E-mail: m.edirisinghe@ucl.ac.uk

 The ORCID identification number(s) for the author(s) of this article can be found under <https://doi.org/10.1002/mame.202200356>

© 2022 The Authors. Macromolecular Materials and Engineering published by Wiley-VCH GmbH. This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

DOI: 10.1002/mame.202200356



Figure 1. Plastic nurdles on the shores of Sri Lanka's coast after a disaster in 2021. Reproduced with permission. Copyright 2021, Mark De Silva.

produced using thermoplastics.^[9] However, the accumulation of plastics, along with other materials, is becoming a serious problem for all countries in the world. These materials occupy a significant volumes in landfills and dumps today. Recently, the presence of huge amounts of plastic fragments in the oceans has been observed, where a considerable part of them come from the streets, going through the drains with the rain, and then going into the rivers and lakes, and then to the oceans.^[10] Currently, more than 99% of plastic is made of fossil fuels and around 19% of greenhouse gases are produced from fossil fuel extraction.^[11] As of 2019, the lifecycle of global plastic manufacture (from cradle to grave) equated to the effects of 189.5 GW coal powered stations on the climate.^[12] By 2050, the impacts are predicted to rise to the effects of 615 coal power plants. As a result, there is a movement around the world for the use of materials that do not harm the planet. At present, the largest amounts of waste are produced in human history, where plastics contribute a majority of it. In 2017, it was estimated that 91% of plastic is not recycled.^[13] The manufacture of plastics has grown exponentially throughout the years, and it is believed that by 2050, there will be more plastic in the ocean than fish and microplastics will contaminate 80% of drinking water.^[14]

In 2020, the global production output of chemical fibers was estimated to reach a value of 80.9 million metric tons, where a yearly increasing trend is shown and predicted.^[15] Chemical fibers are derived from both organic and synthetic polymers, where synthetic fibers equated to over 90% of the total production output in 2020. This paper reviews the production of nanometer to micrometer scaled polymeric fibers to assess its environmental impact from the extraction of materials for polymers and solvents to manufacturing the final polymeric fibers. The study will compare some of the most popular manufacturing processes of polymeric fiber of submicrometer external diameter, to assess envi-

ronmental value and further discuss potential green alternatives, such as the use of hollow polymeric fibers in comparison to regular fibers. The evaluation criteria focus on the manufacture stage in the life cycle of polymeric fibers considering manufacturing processes of polymeric fiber. However, the extraction stage, material processing and end-of-life stages of the life cycle are also explored. The production of hollow fibers utilizing sustainable polymers and solvents via energy-efficient processes such as pressurized gyration may potentially be the most promising route to mass-produce the greenest polymeric fibers.

2. Production of Synthetic Polymers and Solvents

2.1. Synthetic Polymers

Synthetic polymers are manufactured via chemical reactions called polymerization, which occur in many forms where they consist of recurring chemical bindings of individual molecules (monomers).^[16] Variations in parameters such as temperature and pressure result in different chemical bonds, which hold monomers together creating polymers. Combinations of monomers are used to create polymers that show the characteristics of each component, where addition polymerization and condensation polymerization are the two main methods of polymerization.

In addition polymerization, basic hydrocarbons such as ethylene and propylene are converted into polymers by adding one monomer to another in a sequence that continues to elongate.^[16] This is due to the free radicals created as monomers bonding to the chain, which allows for yet another monomer to join resulting in a recurring procedure, which produces thousands of monomers that are bonded jointly. Ethylene and propylene are sort after due to their historical significance in the making of polymers.^[17] They are both derived from petroleum and are often used in the textile industry and to make plastic bottles, from the resulting polymers, polypropylene, and polyethylene, respectively.

Both the polymers mentioned above are called additions as every part of ethylene and propylene are shown in the final polymers, polyethylene, and polypropylene. A chemical reaction that only utilizes just a particular component of a monomer is known as a condensation polymer. This can only take place if the monomer under consideration possesses two or more reactive groups to result in the production of a chain.^[18] In this procedure, the hydrogen in one monomer attaches to the oxygen of another monomer to produce water, which is considered a by-product (condensation). An example of this polymer is Nylon.

Apart from potential hazardous reactions, the polymerization process itself does not significantly affect the environment directly in a negative way, in comparison to the extraction of monomers or the disposal of nonbiodegradable polymers.^[19] Water is the only emission in condensation polymerization. However, it can be hazardous in the instance where the reactions are out of control, causing fire or even explosions. Some materials are also known to strongly react with water to produce gases, such as cyanide, which are lethal at low airborne concentrations. Synthetic polymers mainly obtained from petroleum are a major environmental concern.^[20] The drilling of petroleum can cause major disruptions to wildlands and habitats, along with potential

pollution (such as leakage of toxic substances) from active wells and processing plants. Many polymers consist of various other chemical substances such as stabilizers and flame-retardants to enhance the polymer life and properties.^[21] These additives may be released during disposal to contaminate soil, water, air, and food.

2.2. Solvents

Many of the polymeric fiber manufacture methods such as electrospinning and pressurized gyration require solvents to form polymeric solutions to produce polymeric fibers.^[22] The evaporation of the solvents from the solutions in these methods results in polymeric fibers. The chemical grouping of solvents is dependent on their structure, where they are classified as hydrocarbons, oxygenated or halogenated solvents.^[23] Hydrocarbons such as paint thinner consist of a “carbon skeleton” in the molecules. Oxygenated solvents, such as esters and alcohols, are manufactured via chemical reactions from oil or natural gases. Halogenated solvents consist of halogens such as chlorine. With the exception of solvents, which are fermented alcohols, non-aqueous solvents are produced from fossil fuel sources such as oil and gas.^[24] The extraction of these nonrenewable sources has environmental concerns similar to drilling petroleum.

In the making of polymeric fibers, solvents are selected for polymeric solutions based on previous experience and literature. However, in recent times, strict safety precautions and regulations need to be considered when handling solvents to assess their volatilities, along with features such as boiling point. Organic solvents are effectively classed into either hydrocarbons, alcohols, ethers, or chlorinated solvents.^[25] In general, many solvents are associated with health hazards due to their toxicity to the human body.^[26] The lipophilic feature of some solvents such as hexane and toluene deeply enhances the absorption into humans immediately after dermal contact, inhalation, or oral exposure.^[27] These solvents can badly affect the nervous system along with other organs such as the kidneys and are known to be highly flammable based on their volatility. Metabolism and excretion can occur immediately in the liver and lungs depending on the type of exposure to the solvent. Depending on the solvent, the unmetabolized substance can be deposited in human tissue to affect the human body on a long-term basis. Most organic solvents are categorized as flammable and when mixed with air some of these solvents are also known to explode. Solvent vapor is denser than air, hence the vapor will descend toward the ground and can move large distances while remaining concentrated.^[28] When drawn in large amounts, many solvents cause an unexpected loss of consciousness, whereas halogenated hydrocarbon solvents such as chloroform have been used in medicine such as sedatives. Chloroform is commonly used to dissolve polymers such as polylactic acid (PLA) to produce polymeric nanofiber via methods such as electrospinning.^[29] Here the primary organ which can be affected is the liver in humans which leads to necrosis from exposure.^[30] It also affects the kidneys causing tubular necrosis and swelling of the organs, subsequently leading to the growth of tumors in these organs.^[31] These solvents can also lead to long-term health effects such as cancer. Dichloromethane (DCM), which is commonly utilized to produce polymeric fibers, is a potential hu-

man carcinogen and can cause liver cancer when ingested.^[32] Aromatic hydrocarbons such as toluene are also used in paints, hair dyes, and cleansing agents, where the primary target organ is the central nervous system which can cause headaches and cardiac arrhythmia in humans over long-term exposure.^[33] All ethers such as tetrahydrofuran can cause toxicity to blood lymphocytes, carcinogenicity along with toxicity to the central nervous system in humans.^[34] Alcoholic solvents such as methanol can also cause permanent blindness or death if accidentally ingested. Chronic exposure to solvents in the work environment can also lead to many neuropsychiatric issues. For instance, a large number of painters are known to suffer from alcoholism due to their exposure to alcohol-based solvents in their work environment.^[35] Many organic solvents used in a wide variety of industries, from paint manufacture to engineering, are known or suspected to immensely increase the risk of blindness through the development of cataracts in the eye and also cause loss of hearing.^[36] Furthermore, environmental contamination is also a major risk from the use of toxic solvents, as solvents can readily move great distances, where widespread polluting or poisoning of the soil is not uncommon.

3. Polymeric Fiber Manufacture Methodologies

Many mechanical and chemical methods of polymeric fiber production currently exist. Electrospinning (**Figure 2**) is the most commonly utilized method for the manufacture of submicrometer polymeric fibers, while phase separation, self-assembly, and template synthesis have been regularly utilized to produce polymeric fibers.^[22, 37] The environmental damage and health hazards vary according to each method. This section will review some of the significant methods of polymeric submicrometer fiber manufacture. The energy consumption of each method is estimated considering the forming stages of each method. The data is representative of published literature referenced for each method. Power ratings of the actual equipment used in each method to produce fibers are assessed to calculate energy consumption. However, in the instance where information on the equipment is lacking in the literature, the energy requirements are estimated theoretically.

3.1. Electrospinning

There has been much progress in the development of electrospinning methods in the last decade, where methods such as co-axial and two-stream electrospinning evolved. Electrospinning can be considered as a modified version of melt spinning, where it utilizes an electric force to produce charged strains of polymer solutions or polymer melts.^[38] In the melt spinning process, the polymer is melted for extrusion and then directly solidified. However, electrospinning enhances the extrusion process of the method to obtain thinner polymeric fibers by incorporating electrostatic repulsion. Fibers of various configurations have been produced using over a hundred individual polymers.^[39] However, the development of “green” electrospinning methods remains a challenge mainly due to many polymers used not being water-soluble and a low supply of non-charged polymers that are water-soluble.^[40] The majority of water-soluble polymers consist of

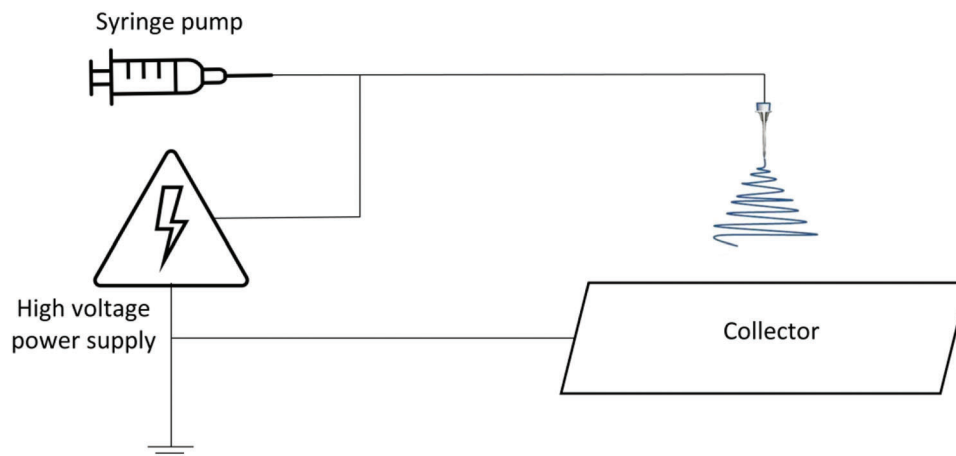


Figure 2. Schematic illustration of a simple electrospinning set up to produce nanofiber.

charged polyelectrolytes, where the viscosities of polyelectrolyte solutions (where salt is not present) are known to be higher due to like charges repelling each other, in comparison to neutral polymer solutions consisting of the same polymer concentration.

Much of the published literature on electrospun polyelectrolytes (solutions), regardless of the presence of salt, utilizes toxic solvents that are harmful to the environment in the spinning process.^[41] The method requires vaporization of the solvent to result in polymeric fibers, where the solvent vapor can cause harm, unless a nonhazardous solvent is utilized in the process. More research is required to be undertaken on either considering the choice of polymer for the selected application or the identification of a less harmful solvent and the optimization of electrospinning conditions. Although water-based polymers will have the lowest impact on the environment, these are mechanically weak and disintegrate rapidly in the environment.^[42] Regardless, there are applications for the use of water-soluble polymers rather than solvent-based polymers. For instance, PVA has been electrospun to form filter media membranes for air filtration applications.^[43] However, there is still a requirement to improve the efficiency and effectiveness of producing air purification filters using this method.^[44] PVA and other water-soluble polymers have also been used to produce oral rapid drug release carriers via electrospinning.^[45] Perhaps the least toxic method of electrospinning is melt electrospinning, which does not utilize any solvents.^[46] Instead, it makes use of heat to melt the polymer for electrospinning, which significantly reduces potential harm caused by toxicity. Electrospinning in general requires high voltages via power units to produce fibers, which subsequently drives up the energy consumption of the process. The use of heat to melt polymers may further add to the already high amount of energy required to produce fibers. There is also a challenge to produce fibers in the nanoscale using melt electrospinning in comparison to solution-based electrospinning where nanofiber can be more easily spun. More focus is required on the optimization of the melt electrospinning process to produce fibers where there are some reports of success.^[47]

A 2021 report by researchers at Columbia University elaborates a “green electrospinning” technique that reduces the ejection of hazardous material into the environment along with the

mitigation of other risks.^[48] Electrospun fibers may also contain traces of solvent after production where the FDA classes some solvents used for electrospinning such as DMF as restricted for use in pharmaceuticals.^[49] According to the report, this green process is scalable and ecoconscious and uses acetic acid instead of traditional solvents like DMF and water-soluble polymers. These green electrospun fibers are incorporated with ceramic nanoparticles and the study concludes that this makes the fibers better than traditionally electrospun fibers in multiple ways. Seemingly, this would reduce negative manufacturing effects by up to six times and improve the mechanical properties of the resulting fiber itself. However, although less volatile, more concentrated acetic acid can also be harmful to humans. To assess the energy consumption of electrospinning, the use of acetic acid in the green electrospinning method described in the report by Columbia University was analyzed to evaluate the overall energy consumption of the method as shown in **Table 1**. The incorporation of ceramic nanoparticles was ignored to evaluate the energy consumption of the green electrospinning process in its most basic form. The Vortex Genie 2 speed mixer utilized in this experiment used a voltage of 120 V along with a current of 0.95 A.^[50] The solvent (acetic acid) was added to the polymer (PLGA/PCL) where it was vortexed for at least 1 h. A standard syringe pump controller such as the Harvard Apparatus PHD 4400 has a power rating of 75 W.^[51] It is assumed a device with a similar power rating is used to produce a flow rate of 0.75 mL h⁻¹ in this step. The calculations in Table 1 estimate the energy consumption to spin 1 mL of polymeric solution using this method. The solution in the study was exposed to a voltage of 10 kV. A typical high-voltage power supply would carry a current of around 3 mA to produce an output voltage of 10 kV.^[52]

3.2. Phase Separation

The phase separation method involves the production of two phases from a homogeneous mixture. Phase separation methods such as the nonsolvent induced separation (NIPS) method and the thermally induced phase separation (TIPS) method have been used to produce polymeric fibers. Phase separation is more

Table 1. Energy consumption estimate of electrospinning.

Step of method	Energy consumption
Spinning of solutions	Power (P) = Voltage (V) \times Current (I) $P = 120 \times 0.95$ $P = 114 \text{ W}$ Energy (E) = Power (P) \times time (t) $E = 114 \times (60 \times 60)$ $E = 410400 \text{ J}$
Syringe pump infusion	Flowrate (mL s^{-1}) = $0.75 / (60 \times 60)$ Flowrate = $2.0833 \times 10^{-4} \text{ mL s}^{-1}$ Time (t) = $1 / (2.0833 \times 10^{-4})$ $t = 4800 \text{ s}$ $E = P \times t$ $E = 75 \times 4800$ $E = 360000 \text{ J}$
Power unit	$P = V \times I$ $P = 10000 \times 0.003$ $P = 30 \text{ W}$ $E = P \times t$ $E = 30 \times 4800$ $E = 144000 \text{ J}$
Total = $9.14 \times 10^5 \text{ J}$	

commonly utilized to produce membrane technology such as hollow fiber membranes.^[53] In NIPS, the polymer–solvent solution is placed in a coagulation bath containing a nonsolvent. Once immersed, mutual diffusion between the solvent and nonsolvent leads to phase separation due to the change in composition which results in polymer precipitation and membrane formation. Thermally-induced phase separation involves the manipulation of the solubility of polymers by lowering the temperature as the polymer separates out of their solvent. Initially, the polymer is required to be dissolved into a solvent at a high temperature before being solidified via freezing (gelation). The dissolving is typically done at a temperature higher than the melting point of the polymer to produce a homogenous mix.^[54] The gelation

is considered to be the most difficult step in the process as the porosity and morphology need to be controlled.^[55] The polymer solution also needs to be cast in fiber form when cooling to obtain fibers while the solvent is extracted. Freeze-drying is often utilized to obtain optimum porosity where this step can last up to 1 week.^[56] Due to the requirement of gelation and freeze drying to obtain porosity, this method requires a considerable amount of energy for fiber manufacture as it involves the manipulation of temperature. Toxic solvents such as dimethylformamide (DMF) and dimethylacetamide (DMA) are commonly used to dissolve petroleum-based polymers using this method.^[57] However, only a few polymers such as PLA have been utilized to produce fibers with phase separation.^[58]

A French report presents an environmentally improved phase separation method that makes use of supercritical carbon dioxide for drying instead of freeze-drying.^[59] **Figure 3** portrays a schematic diagram of the method in this report, which incorporates the use of supercritical CO_2 . A Life Cycle Assessment of the traditional method in comparison to this new method has shown a 50% reduction in environmental impact according to the study. To assess the energy consumption of the method described in this report, the processes of the technique are tabulated as shown in **Table 2**. The study utilized PLA which was magnetically stirred with 1,4-dioxane at 50°C to obtain a concentration between 5% wt to 10% wt.^[59] Due to the requirement of heat to mix the solution, it is assumed that a hot stirrer is used for this step rather than a vortex speed mixer. It is also assumed the solution was stirred for at least an hour, similar to the electrospinning method using a standard 500 W magnetic hot stirrer.^[60] Water was then added to the solution for the phase separation process, where 1 mL samples of the solution were then cooled to -20°C , -80°C , and -196°C . 1,4-Dioxane has molar heat capacity of $150 \text{ J mol}^{-1} \text{ K}^{-1}$. Since the solution is relatively dilute, where the solvent dominates the solution, it can be assumed that $c_p \approx c_{p,\text{solvent}}$, where " c_p " is the (molar) heat capacity of the mixture and " $c_{p,\text{solvent}}$ " is the molar heat capacity of the solvent. 1,4-dioxane has a density of 1030 kg m^{-3} and it is assumed that the polymeric solution has a density close to this value considering

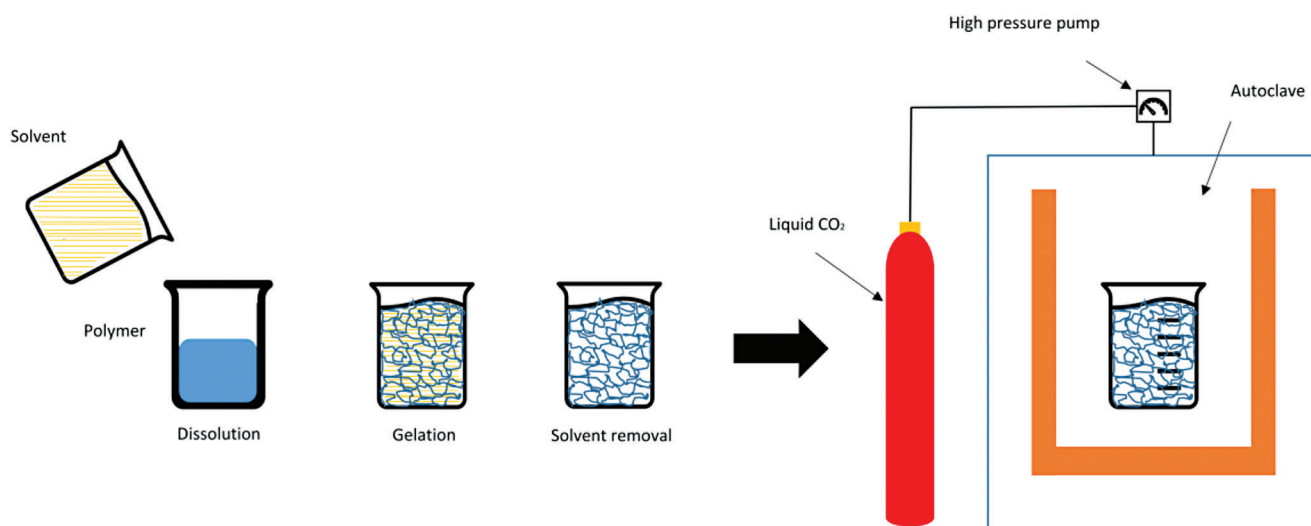


Figure 3. Schematic illustration of phase separation process including the use of supercritical carbon dioxide.

Table 2. Energy consumption estimate of phase separation.

Step of method	Energy consumption
Mixing of solution	$E = P \times t$ $E = 500 \times (60 \times 60)$ $E = 1800000 \text{ J}$
Sampling cooling	1,4-dioxane has a heat capacity of $150.65 \text{ J mol}^{-1} \text{ K}^{-1}$ and a molar mass of 88.11 g mol^{-1} . $c_p = \frac{150.65 \text{ J mol}^{-1} \text{ K}^{-1}}{88.11 \text{ g mol}^{-1}}$ $c_p = 1.71 \text{ J g}^{-1} \text{ K}^{-1}$ To cool samples to $-80 \text{ }^\circ\text{C}$ from $50 \text{ }^\circ\text{C}$: $Q = mc_p \Delta T$ $Q = 1.03 \times 1.71 \times 130$ $Q = 229 \text{ J}$
Cold storage	$E = P \times t$ $E = 8000 \times (12 \times 60 \times 60)$ $E = 345.6 \times 10^6 \text{ J}$
Cold storage after ethanol submersion	Assuming minimal power consumption (at 100 W): $E = P \times t$ $E = 100 \times (2 \times 60 \times 60)$ $E = 720000 \text{ J}$
Autoclave	PLA has a specific heat capacity of $1800 \text{ J kg}^{-1} \text{ K}^{-1}$. $Q = mc\Delta T$ $Q = 1.03 \times 10^{-3} \times 1800 \times 31$ $Q = 57.5 \text{ J}$
Application of pressurized CO_2	$E = P \times t$ $E = 75 \times 1000 \times (4 \times 60 \times 60)$ $E = 1.08 \times 10^9 \text{ J}$
Total	$1.43 \times 10^9 \text{ J}$

the solution is relatively dilute. Therefore, a volume of 1 ml of the polymeric solution should have a mass of around 1.03 g. After cooling the samples were left at the above conditions in cold storage for 12 h, before being soaked in liquid nitrogen for at least 5 min. Ultralow temperature (ULT) freezers are typically utilized for biomedical processes such as cold storage. Typical ULT freezers have a power consumption of around 8 kWh per day at a temperature of $-80 \text{ }^\circ\text{C}$.^[61] The samples were then submerged

in ethanol precooled to $-20 \text{ }^\circ\text{C}$, to extract the solvent in a 2 h cold storage at $4 \text{ }^\circ\text{C}$. Domestic fridge power consumption is typically between 100 and 250 W.^[62] To conclude, the samples were left in an autoclave at $35 \text{ }^\circ\text{C}$ and pressurized with CO_2 at 15 MPa for 4 h. The energy consumption of this step of the process is estimated considering the specific heat capacity of PLA. It is assumed that the samples were immediately placed in the autoclave after refrigeration. The liquid CO_2 was preheated with the use of a heat exchanger before being continuously pumped with the use of a high-pressure membrane pump at a rate of 1 kg h^{-1} . The high-pressure pump used in this study (Milton Roy Europe) has a maximum motor power of 75 kW.^[63] According to the specifications of the pump, the pump would have to perform on maximum motor power to deliver a liquid CO_2 flow rate of 1 kg h^{-1} .

3.3. Self-Assembly

As the name suggests, this involves molecules arranging into patterns via noncovalent forces such as electrostatic reactions and is also one of the bottom-up material production processes.^[22] It (see **Figure 4**) is considered to be a good method to produce fibers lower than 100 nm where the primary mechanism depends on intermolecular forces. It also makes use of gelation where the polymer solution is maintained at the gelation temperature before the solvent is removed resulting in the formation of polymeric fibers. The main limitation of this process is the complexity along with low productivity and lack of control of fiber dimensions.^[58] It is also limited to fibers that can be formed from active molecules that can self-assemble spontaneously.^[64] Therefore, the material choices to produce fibers using this method are limited. Its environmental effects are similar to phase separation due to the similarity of the gelation process and the use of solvents in both methods.

When estimating the energy consumption of this process, it can be assumed that the magnetic stirring, gelation, and solvent removal steps of the process will have a similar energy consumption in the cooling steps as shown in the phase separation method. Assuming the same polymer and solvent with the same consistency as were used as in Table 2 an estimated

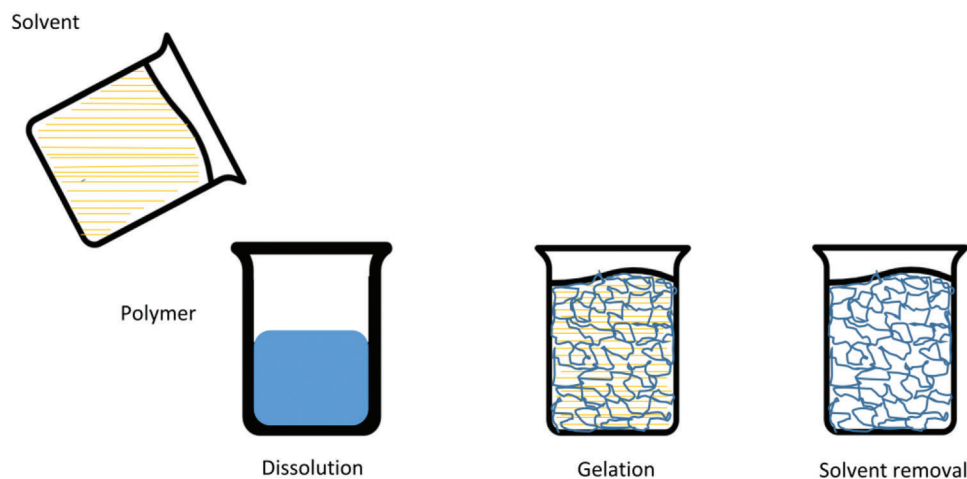


Figure 4. Self-assembly process.

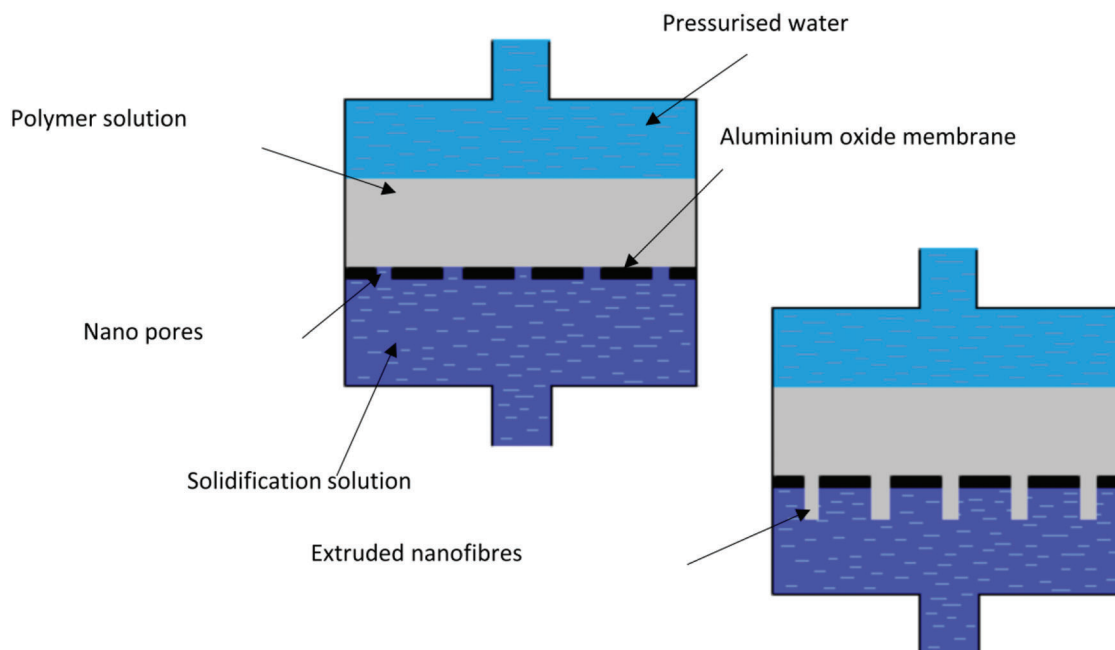


Figure 5. Template synthesis process.

total energy consumption of 348.12×10^6 J is deduced for the self-assembly method. The types of interactions dictate the intermolecular forces. Van der Waals forces, electrostatic interactions, hydrophobic and hydrogen bonding are the primary drivers of self-assembly. Intermolecular forces are ubiquitous in nature. However, these forces can be obtained by other means. For instance, to obtain electrostatic interactions, ions can be produced by methods such as electron ionization to charge atoms or molecules in preparation for self-assembly. Considering such methods used to produce intermolecular forces may significantly further drive up the total energy consumption of the self-assembly method. For example, when using field-directed assembly, an electric field is used to promote interactions between nanoparticles into long continuous chains.^[65] Depending on the equipment used, along with the time and magnitude, the voltage is maintained for during this step of the process, the total energy consumption will be larger than 348.12×10^6 J.

3.4. Template Synthesis

This process (Figure 5) incorporates the use of chemical or electrochemical oxidative polymerization to produce fibers of different materials such as metals and polymers.^[22] It employs the use of a template (or cross-sectional mold) of the required material and structure to produce polymeric fibers. When producing polymeric nanofibers, a metal oxide template or membrane with submillimeter scaled pores is utilized to extrude fibers by passing the polymeric solution through one side of the membrane to get in contact with the solidifying solution on the other side (as shown in Figure 5). A drawback of this method is that it is incapable of achieving long fiber lengths, although multiple diameters are feasible to obtain by changing the templates. Regardless of this drawback, template synthesis is the most com-

Table 3. Energy consumption estimate of template synthesis.

Step of method	Energy consumption
Preparation of polymeric solutions	$E = P \times t$ $E = 500 \times (60 \times 60)$ $E = 1800000$ J
Synthesis of fibers	$E = P \times t$ $E = 90 \times 30$ $E = 2700$ J
Total =	1.80×10^6 J

monly utilized method to manufacture fibers and hollow carbon fibers.^[66] The water pressure is the primary driver of extrusion to form fibers in this process. Therefore, it is a relatively less energy-consuming method in comparison to most of the other methods listed in this section. However, the need for solvents remains.

A 2002 experiment to produce polyacrylonitrile (PAN) fibers using template synthesis is analyzed in Table 3 below to estimate its overall energy consumption.^[67] PAN (10.976 g, $M_w = 120\,000$) was dissolved in DMF (50 mL) with stirring at 70 °C to form an 18 wt% precursor solution. A mixture of 40 wt% DMF and 60 wt% deaerated Milli-Q water was used as the solidifying solution. It is assumed a standard 500 W magnetic hot stirrer was utilized in this process, to stir both solutions at the same time in an hour. The fibers were synthesized by subjecting the polymeric solution to a water pressure of 0.1 MPa with the use of a water pump. An anodic aluminum oxide membrane with a pore diameter of about 102 nm was used as a template. A standard pressure booster pump to produce a pressure of 0.1 MPa requires a wattage of 90 W.^[68] It was assumed that a similar device was utilized in the experiment and the solution was subject to a pressure for no more than half a minute.

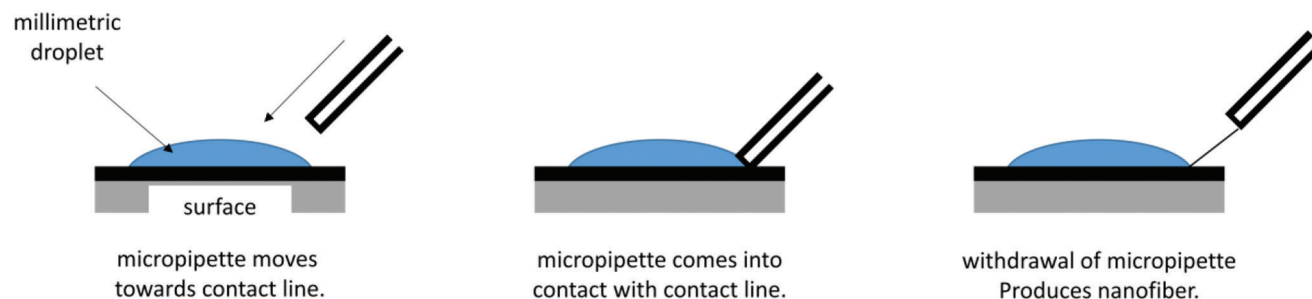


Figure 6. Drawing method to produce fibers.

Table 4. Energy consumption estimate of drawing method.

Step of method	Energy consumption
Production of 20% PVA solution for drawing.	$E = P \times t$ $E = 6 \times (24 \times 60 \times 60)$ $E = 518400 \text{ J}$
Total	$5.18 \times 10^5 \text{ J}$

3.5. Drawing

This process (see **Figure 6**) has the ability to produce long lengths of fibers in a single process, where the process just needs a micropipette to draw out polymeric fibers from either a polymer solution or melted polymer.^[69] The solvent is evaporated by extrusion which causes high surface area, however, a cooling step might be necessary in the case of melt extrusion. The process can be slow as the micropipette gently pulls the liquid at a very low speeds of around 10^{-4} m s^{-1} to extrude fibers one at a time.^[22] This is repeated several times to draw fibers from the same droplet of polymeric solution. Another limitation is that only materials that are viscoelastic and can withstand stresses and strains of drawing can make use of this process. Regardless of these drawbacks, this technique is a very energy efficient method in that a polymeric solution is used instead of melt extrusion. **Table 4** estimates the energy consumption of an experimental study from 2011, where the finest PVA fibers were drawn at a rate of 0.03 m s^{-1} from a polymeric solution concentration of 20%.^[70] Due to the water solubility of PVA, it is assumed a magnetic stirrer is used for 24 h to produce the solution for this process. A standard 6 W magnetic mixer with no heating is assumed to have been used for this part of the process.^[71]

3.6. Gyration Methods

Gyration-based methods such as centrifugal spinning and pressurized gyration (PG) primarily make use of the centrifugal force from the rotation of the vessel to extrude polymeric fibers out of the nozzles in the vessel.^[72] In PG, the simultaneous application of gas pressure helps fiber generation (see **Figure 7**). These methods make use of solvents to produce fibers, except in the case of pressurized melt gyration where it uses polymer in liquid state rather than in a polymer–solvent solution.

Pressurized gyration (and centrifugal spinning) is one of the few methods that has the ability to mass-produce submicrome-

ter diameter polymeric fibers swiftly.^[73] This is subsequently a more energy-efficient technique in comparison to most of the other processes currently utilized. This method can make use of all of the polymeric solutions in the vessel to convert to fibers within a minute of the system starting to run. This also contributes to making its power usage considerably lower in comparison to other methods. A 2019 study in fluid behavior during the use of polyethylene oxide (PEO) and deionized water to manufacture via pressurized gyration is analyzed as shown in **Table 5**.^[74] The application of pressure is ignored in this energy estimation, as nitrogen gas from a cylinder is manually released via a pressure control valve, which does not require any energy input. The study claims a magnetic stirrer at ambient temperature was utilized in this process for 24 h. A standard 6 W magnetic mixer with no heating is assumed to have been used for this part of the process. A typical electric motor capable of producing enough torque to spin the vessel of the pressurized gyration system up to 10 000 rpm has a power rating of 21.2 W.^[75] A 2019 study claims that the method produces a yield of 3.2 kg of fiber an hour (0.89 g per second) when running at full speed.^[76] PEO is utilized to produce solutions of multiple weight percentages, where 21% wt was the largest percentage. This would equate to 0.21 g of PEO in 1 mL of solution at 21% concentration. In theory, 0.21 g of polymer requires less than 1 s for extrusion into fibers, as the paper suggests a yield of 3.2 kg h^{-1} was achieved. However, it is assumed that the motor is run for around 30 seconds for all of the polymeric solution to be used during the gyration process.

4. Comparison of Fiber Manufacture Techniques

The UK hosted the 26th UN Climate Change Conference of the Parties (COP26) in Glasgow on the 31st of October 2021. The COP26 summit brought groups together to accelerate action towards the goals of the Paris Agreement and the UN Framework Convention on Climate Change. Energy consumption, and in particular the burning of fossil fuels, is the main source of human-induced greenhouse gas emissions.^[77] According to published literature, there are more attempts to improve the environmental effects in electrospinning than in any other polymeric fiber manufacturing method. Perhaps this is due to this method having the most room for improvement, along with it being the most commonly used method to fabricate polymeric fibers. **Table 6** reviews the potential environmental effects considering the hazards, energy consumption, and efficiency of each method discussed. The environmental impacts are color coded

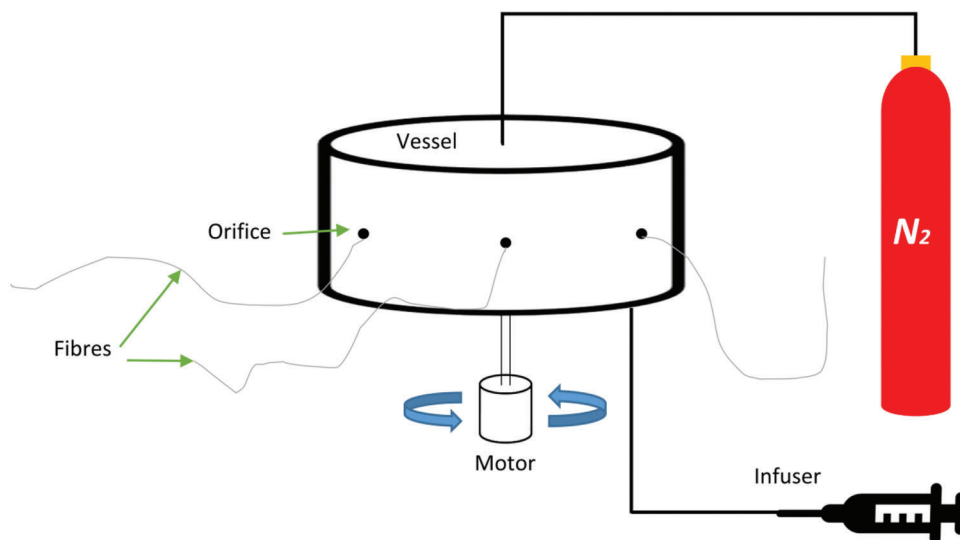


Figure 7. Pressurized gyration system.

Table 5. Energy consumption estimate of pressurized gyration.

Step of method	Energy consumption
Preparation of polymeric solution	$E = P \times t$ $E = 6 \times (24 \times 60 \times 60)$ $E = 518400 \text{ J}$
Gyration of the vessel	$E = P \times t$ $E = 21.2 \times 30$ $E = 636 \text{ J}$
Total	$5.19 \times 10^5 \text{ J}$

according to a hazard scale, along with the score for efficiency to obtain a final score to compare each method.

The energy consumed only during the actual manufacture of fibers including the dissolving of polymer into solvents for each method was evaluated. Energy in dissolving polymers to solvents can also take up to days for some polymeric solutions, depending on concentration. However, the assumption was made that this step of the method was the same in terms of energy consumed for each of the methods, to maintain an unbiased analysis. Due to lack of information, humidity and temperature control were neglected when evaluating energy consumption of all methods, however, these can be two major variables in controlling fiber morphology and properties.

Electrospinning required an estimated total of $9.14 \times 10^5 \text{ J}$. This however can vary depending on the parameters, such as voltage, volumes of polymeric solution, and flowrate used to spin fibers. The investigation made use of relatively high voltages, whereas some polymers are spun at lower voltages, and may also require lower flow rates. These parameters will affect exactly how much energy is consumed in these methods. The time under which the solutions are exposed to electricity, during manufacture, is an important factor for the energy consumption in this process. The amount of solution used along with the flow rates considered for electrospinning will primarily dictate the amount

of time required. The method was judged to be moderately hazardous but reliable overall regardless of the difficulties associated with the use of the technique due to its efficiency.

Phase separation was shown to be the most energy-consuming method. Table 6 shows that this method was the least scoring considering its hazards and overall efficiency. The energy estimation of the phase separation method also only took into consideration the actual energy required theoretically to cool the samples to $-80 \text{ }^\circ\text{C}$, considering the specific heat. The information regarding the appliance used for this step of the process was not indicated. In reality, this step of the process will consume more energy when taking the power rating of the equipment of the cooling process is taken into account. The length of time the samples were left in low temperatures significantly impacted the energy consumption as this step of the process can take up to a week in some cases under different freeze-drying temperatures. In addition, the use of the autoclave along with pressurized CO₂ drastically increased power consumption. However, according to the 2018 study, the use of supercritical CO₂ is said to have up to a 50% reduction on the effect of the environment than the conventional method. This indicates that the traditional method of phase separation may produce an even higher environmental impact than the use of supercritical CO₂. Supercritical fluids are considered green solvents as it is used in extraction processes and abide by the principles of green chemistry.^[84] However, the use of supercritical CO₂ seems to require a vast amount of energy due to the use of a high-pressure membrane pump and is also not the simplest route due to the other complications.^[85, 86] Besides this, the actual energy consumption estimation for this method is most likely higher, mainly due to the evaluation of thermal energy to increase or decrease temperature of only the polymeric solution. The use of the equation heat energy = (mass \times specific heat \times change in temperature), estimates the energy required to change the temperature of the polymeric solution in an ideal 100% efficient scenario. A more accurate measure is to assess the power rating of the equipment used in this step of the process for the phase separation method, where instead thermal

Table 6. Comparison of methods (Hazard scale—low (4), moderate (3), high (2), very high (1)). Efficiency scale 1 to 5, where 5 is the most efficient.

Production method	Energy	Analysis	Hazard	Efficiency	Score
Electrospinning	9.14×10^5 J	The use of very high voltages, along with potentially hazardous solvents can be highly dangerous, unless the correct safety precautions are followed. ^[78] Due to flowrates being small, the method takes time to produce polymeric fibers from the same amount of solution in comparison to methods such as pressurized gyration. ^[79] In comparison, this subsequently results in high power consumption. Other issues also include solution clogging the needle. ^[80] Scaling up this method for mass production can cause the overall equipment to be more complex and expensive. ^[58]	3	4	12
Phase separation	1.43×10^9 J	The use of solvents, along with extreme temperatures and pressures can be highly hazardous. Furthermore, this method remains a laboratory scale process despite its simplicity. ^[81] It is only limited to a few polymers. ^[82] Temperatures need to be varied which subsequently require more energy to do so.	1	2	2
Self-assembly	348.12×10^6 J	Similar to phase separation, the use of solvents, along with extreme temperatures and pressures can be highly hazardous. The necessity of a cooling procedure in the instance of melt spinning may require more energy usage that in the case of dry spinning. The complexity of the procedure influences the low efficiency score. ^[69]	2	2	4
Template synthesis	1.80×10^6 J	The requirement of solvents for the extrusion process can be hazardous. Regardless, it can be argued that this method is a simple and environmentally friendly technique of producing fibers, as water pressure is the primary driver of producing the fibers via extrusion. However, the method cannot produce long continuous fibers. ^[82]	4	3	12
Drawing	5.18×10^5 J	The requirement of solvents for the drawing process is hazardous. However, it has the potential to draw fibers from a polymer melt rather than a polymer solution, although the melting of polymers will cause the overall energy consumption due to manufacture to rise. ^[69] However, drawing is probably the simplest method of producing long single polymeric fibers that require the least energy, as all it requires is a micropipette to draw fibers. ^[82] However, the very low productivity is a major disadvantage. ^[22]	4	1	4
Gyration methods	5.19×10^5 J	The requirement of solvents to process fibers can be environmentally hazardous. It can be argued that the mass-producing features and fast processing of polymeric solutions into fibers can be make this the more environmentally advantageous method. ^[83] The pressurized gyration method works best with water soluble polymers. This method can deliver a very high quantity of fibers within a minute whereas other methods discussed can take up to days.	4	5	20

energy was assessed using the heat energy equation in Table 2. Similar to phase separation, the self-assembly method also requires changes in temperature and storage at low temperatures, which makes this method more energy consuming. An estimated 348.1×10^6 J of energy is required to produce polymeric fibers using this method, where the estimation did not include the energy required for potential methods to promote the interaction between atoms and molecules. Considering such processes for the self-assembly method would most likely show a higher estimation of the energy consumed.

At 1.8×10^6 J and 5.18×10^5 J respectively, template synthesis and drawing require low amounts of energy to produce fibers. However, in the instance that only ambient temperatures are required to stir polymeric solutions, these methods are likely to require even lower amounts of energy than electrospinning and pressurized gyration. Pressurized gyration and template synthesis are probably more convenient to produce fibers, due to its

relatively quick production of fibers in comparison to drawing or electrospinning. However, electrospinning scores more than template synthesis in the efficiency scale on Table 6 as template synthesis cannot produce long fibers. Considering the drawbacks of the methods evaluated in this study, gyration-based methods show the most promise in delivering fibers efficiently and for an environmentally friendly bias. This is mainly due to its fast-processing features and relatively simple procedure in producing fibers.

Figure 8 displays an energy comparison pie chart to produce polymeric fibers from each method listed previously. It is shown that self-assembly, template synthesis, drawing, and gyration-based methods combined only require a very small fraction (less than 0.3%) of the amount of energy in comparison to phase separation. However, considering the total lifecycle for polymeric fibers manufacturing methods may show different results in terms of energy consumed in their total cycle. For instance, when

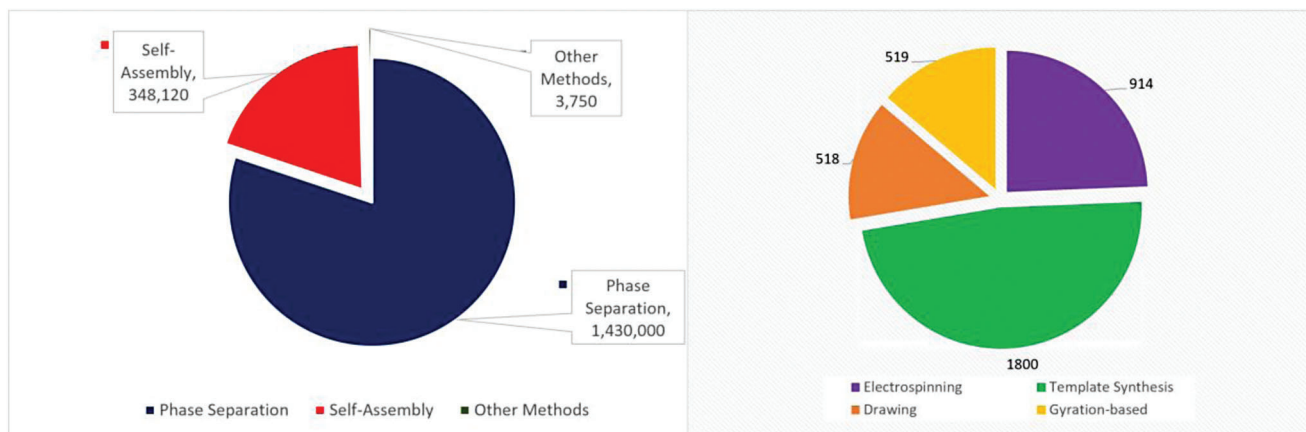


Figure 8. Energy consumption comparison to produce fibers from 1 mL of polymeric solution (in KJ).

considering the process of obtaining nitrogen gas via fractional distillation of liquid air, the overall energy consumption of producing polymeric fibers using pressurized gyration may be significantly higher.^[87] However, nitrogen is not essential and pressure can be imparted using compressed air. Taking into consideration parameter control techniques, such as a dehumidifier for humidity control (which can be critical to produce polymeric fibers with desired characteristics), can further elevate energy consumption during manufacture.

5. Cost Assessment of Polymeric Fiber Manufacture Methods

The average electricity costs in the UK are at 21.0 p kW h⁻¹ as of March 2022.^[88] Considering this and the amount of time taken to complete each step of the polymeric fiber manufacture methods, the energy cost to produce fibers is estimated as shown in **Table 7**. 1 kWh equates to 3.6 × 10⁶ J, therefore, the costs are estimated by dividing the energy values in Joule by 3.6 × 10⁶ and multiplying this value by the unit cost of electricity in the UK (£0.21 kW h⁻¹).

The cost estimations are likely to be higher in real situations when considering other parameters involved, such as controlling temperature and humidity. Also, other factors such as method of stirring polymeric solutions can play a significant role in determining the energy and cost requirements. Regardless, the overall cost ratios of the methods would be more or less the same as shown in **Figure 9**. Considering the cost estimations are to produce polymeric fibers from 1 mL of solution, it can be shown that pressurized gyration is the most cost-effective and efficient technique to mass-produce polymeric fibers.

It is forecasted that the UK increases electricity costs, where it would rise from £0.21 kW h⁻¹ to £0.28 kW h⁻¹ by April 2022.^[88] As of 2020, the majority of energy to generate electricity is sourced from gas which has shown an exponential rise price since 2020 and accounted for 80% of the total electricity cost in the UK.^[89] According to the 2021 energy brief, 56.9% of the UK's power grid is generated by nonrenewable energy sources such as fossil fuels and nuclear energy.^[90] However, the use of non-renewable energy sources has shown a decline in recent years in the UK, although, on a global scale, renewable energy is still dwarfed by fossil fuel power. Considering recent world events,

the energy costs are estimated to further increase globally. This further justifies the need to deliver energy-efficient means of mass-producing polymeric fibers.

6. Future Perspectives for Green Alternatives

Ironically, the use of biodegradable plastics does not seem to solve ocean-related pollution problems, as these types of plastics do not decompose in ocean waters due to cold ocean temperatures.^[91] As a result, they usually end up either floating or disintegrating to microplastics, which endangers marine life. It is also difficult to conclude that bioplastics are more environmentally friendly than regular plastics when considering all aspects of their life cycle including the use of land and pesticides, along with energy consumption, emission of greenhouse gases, and recyclability.^[92] As researchers are focused on developing greener methods of manufacture, biopolymers itself may not hold promise to support the reduction of plastic pollution, along with the reduction of the carbon footprint. Therefore, it can be suggested that biodegradable polymers cannot resolve all pollution issues. Hence, to refine polymeric fiber production, the application of naturally derived polymers, additives, and other solutions need to be taken into consideration in the manufacture of fibers.^[93]

6.1. Bioplastics and Biodegradable Plastics

There are various origins for natural polymers, where as far as the biomaterials field is concerned, natural polymers are sourced from microorganisms, plants, and animals. Due to the benefits, natural polymers offer, especially environmentally, they are a considered good substitute for fiber production, especially for biomedical-related applications. Some of the major benefits of utilizing natural polymers are the fast integration onto wounded sites and resemblance to the host tissue, along with its biocompatibility and biodegradation. It also has the potential to degrade by enzymes and the capacity to react with biological structures in a controlled method.^[94] At present, there are a large number of natural polymers that are compatible with current polymer fiber manufacturing methods, which have been extensively researched in the recent past.^[37]

Table 7. Cost evaluation of polymeric fiber manufacturing methods to produce fibers from 1 mL of polymeric solution.

Method	Step of the process	Cost calculations
Electrospinning	Spinning of solution	$410000 \div 3.6 \times 10^6 = 0.114 \text{ kWh}$ $\text{£}0.21 \times 0.114 = \text{£}0.024$
	Syringe pump infusion	$360000 \div 3.6 \times 10^6 = 0.1 \text{ kWh}$ $\text{£}0.21 \times 0.1 = \text{£}0.021$
	Power unit	$144000 \div 3.6 \times 10^6 = 0.04 \text{ kWh}$ $\text{£}0.21 \times 0.04 = \text{£}0.008$
	Total	£0.053
Phase separation	Hot stirrer	$1800000 \div 3.6 \times 10^6 = 0.5 \text{ kWh}$ $\text{£}0.21 \times 0.5 = \text{£}0.105$
	The cooling step cost calculations exclude the energy required to cool the polymeric solution before storage in an ultralow temperature freezer	$345.6 \times 10^6 \div 3.6 \times 10^6 = 96 \text{ kWh}$ $\text{£}0.21 \times 96 = \text{£}20.16$
	Ethanol cold storage	$720000 \div 3.6 \times 10^6 = 0.2 \text{ kWh}$ $\text{£}0.21 \times 0.2 = \text{£}0.042$
	Use of supercritical CO ₂ , where the energy used to maintain a temperature of 35 °C is ignored in the calculation.	$1.08 \times 10^9 \div 3.6 \times 10^6 = 300 \text{ kWh}$ $\text{£}0.21 \times 300 = \text{£}63$
	Total	£83.31
Self-assembly	The self-assembly process requires a total energy cost of £20.307, as previously assumed stirring, gelation and solvent removal steps of the phase separation process used for this technique.	
Template synthesis	Hot stirrer	$1800000 \div 3.6 \times 10^6 = 0.5 \text{ kWh}$ $\text{£}0.21 \times 0.5 = \text{£}0.105$
	Pressure booster pump	$2700 \div 3.6 \times 10^6 = 0.00075 \text{ kWh}$ $\text{£}0.21 \times 0.00075 = \text{£}0.0002$
	Total	£0.1052
Drawing	Hot stirrer	$518400 \div 3.6 \times 10^6 = 0.144 \text{ kWh}$ $\text{£}0.21 \times 0.144 = \text{£}0.03$
Gyration-based	Hot stirrer	$518400 \div 3.6 \times 10^6 = 0.144 \text{ kWh}$ $\text{£}0.21 \times 0.144 = \text{£}0.03$
	Motor	$636 \div 3.6 \times 10^6 = 0.00018 \text{ kWh}$ $\text{£}0.21 \times 0.00018 = \text{£}0.000038$
	Total	£0.03

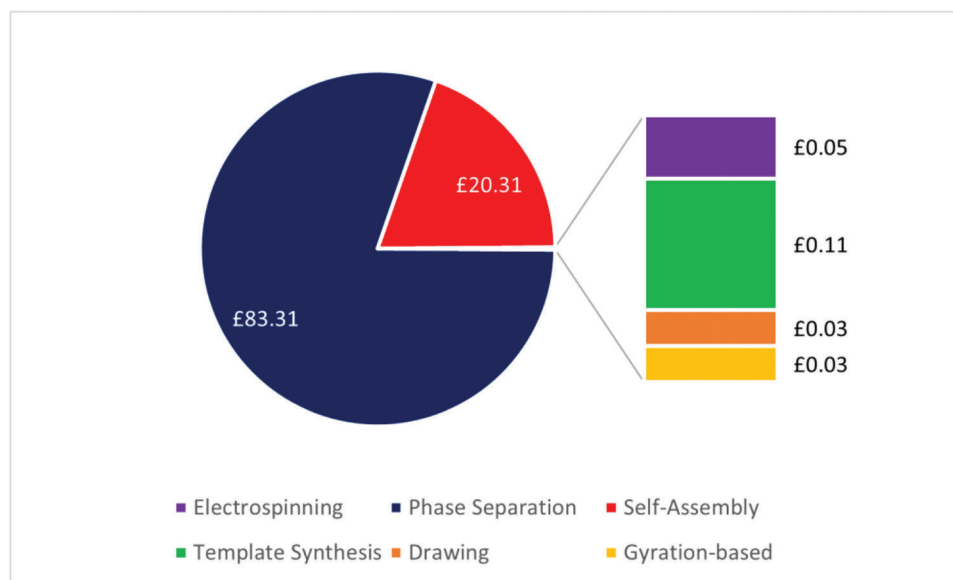


Figure 9. Cost comparison of fiber production methods.

In general, biopolymers are thought to be ecofriendlier than traditional polymers. However, a 2010 study by the University of Pittsburgh concluded that this is not particularly factual when the entire material life cycle was analyzed.^[95] The research contrasted seven traditional plastics, along with four bioplastics and a single plastic produced from both fossil fuels and renewable resources. The investigators discovered that bioplastics manufacture produced a larger quantity of pollutants when fertilizers and pesticides were taken into account. These chemicals are utilized in growing crops and chemical processing which are required to convert organic material into bioplastic. It was also found that bioplastics promote ozone depletion more than regular plastics and also require large-scale land use. However, bioplastics do emit a remarkably lower amount of greenhouse gas emissions in comparison to traditional plastics. There is no resulting increase in carbon dioxide when bioplastics break down as they are produced from the same quantity of carbon dioxide. A 2017 report concluded that substituting traditional plastics with corn-based PLA would reduce greenhouse gas emissions by 25% in the USA.^[92] The report also determined that the production of traditional plastics from only renewable energy sources can reduce emissions by 50–75%. Although the biodegradability of biopolymers is beneficial, most of these biopolymers require high-temperature industrial composting provisions, which is uncommon and only a few cities seem to possess such provisions. Subsequently, these biopolymers culminate in landfills, where there is risk of methane being released from them, a greenhouse gas known to be 23 times more potent than carbon dioxide. Solar UV radiation is necessary to trigger the photo-oxidation degradation process of most polymers, which occurs through a radical chain mechanism that results in bond cleavage and a reduction in molecular weight.^[4] Polymers discarded in landfills are unlikely to have enough access to UV radiation. Bioplastics (and biodegradable) when discarded incorrectly can contaminate recycled plastics and can impair recycling infrastructure. For instance, if PET (polyethylene terephthalate) which is common plastic utilized to produce bottles, is exposed to bioplastics, the whole lot may be declined and end up in a landfill. Therefore, there is need for separate streams to appropriately discard both biodegradable plastics and bioplastics. Bioplastics are produced from natural materials and hence, composting of bioplastic components can make soil fertile, due to the absence of artificial chemicals.^[96] The land need for the production of bioplastics may hinder food production, as the crops that are used to manufacture these plastics can be utilized for food which is known to be in a shortage. In 2017, a joint report of European environmental organizations, estimated that the area of land required to keep up with global demand would equate to more than 1.3 million acres of land by 2019.^[97] This is an area larger than Denmark, the Netherlands and Belgium put together. It can also be noted that the petroleum required to maneuver farming machinery will also emit greenhouse gases. Bioplastics can also be relatively costly. For instance, PLA can be up to 50% more expensive in comparison to similar traditional plastics due to the intricate method utilized to convert corn or sugarcane into the building blocks for PLA.^[93] Regardless, the costs of bioplastics have slowly reduced as businesses and researchers evolve more greener and efficient techniques for manufacturing bioplastics. The production of bioplastics such as PLA, commonly used to

make nanofibers for various applications, does not require the process of discovery, acquisition, and transportation of hydrocarbons. This results in the use of fewer fossil fuels and produces up to 67% less greenhouse gases during manufacture.^[98]

The manufacture of biodegradable plastics can be costly. However, considering the clean-up costs along with the lower negative environmental effects, biodegradable polymers are the better option. They also require less energy for production in comparison to regular plastics. Crude oil (petroleum) is a major element in the production of traditional plastics. The extraction and refinement of crude oil significantly affect the environment. According to the British Plastic Federation, it is believed that 4–6% of oil is used in the manufacture of plastics in Europe alone.^[99] Biodegradable plastics use up to 20% renewable materials in its production when compared to traditional plastics. Current research is being undertaken on biodegradable plastics, where in the future, these plastics will only release the same quantity of energy used in manufacture.^[100] Nonpetroleum-based plastics such as PLA, that are made from plants such as corn and sugarcane also curtail carbon dioxide as they do not emit an excess amount of CO₂ during decomposition.^[101] The use of plant oil as renewable feedstock for the synthesis of polymers has also been recently researched for development.^[102]

Global plastic production reached 381 million tonnes in 2015.^[103] Assuming that a majority of these plastics are for the making of plastic bags and bottles, the manufacture of such quantities of plastic would emit a staggering 2.3 billion tons of CO₂ into the earth's atmosphere.^[104] This is equivalent to the emissions from 87 million vehicles every year. They also release an inebriating greenhouse gas when burnt at landfills. These calculations are likely to be underestimated as new research suggests CO₂ emissions have risen considering the plastic production in countries that utilize large amounts of coal.^[105] Moving to the use of bioplastics can significantly lower the emission of greenhouse gasses and subsequently reduce the impact of its effects, such as extreme flooding and desertification. In terms of recycling, biodegradable polymers are quick to decompose and can be rather easily broken down via an organic procedure. These are also nontoxic and help with the reduction of landfill-related issues. The recycled waste product can also be utilized as compost or for biogas. Biodegradable polymers disintegrate in the space of a few months, based on the materials utilized to produce the polymer and method of disposal. It also requires less space for disposal in the event where it does not fully decompose. The disposal of traditional plastics results in the release of other toxic chemicals and various other pollutants to the environment. These chemicals are known to easily harm marine life, ecosystems and also affect human health. For instance, Bisphenol A, which is an important ingredient in the production of plastics, is linked with the endocrine disruption, which is immensely damaging to the human reproductive cycle.^[106] Bisphenol A is commonly utilized in many polymer products such as baby products and food containers.^[107] Other chemicals in the production of regular plastics have also been associated with diseases such as cancers. The transfer to biodegradable plastics will significantly reduce the release of such lethal by-products into the natural environment and support in the delivery of a “greener” future. Biodegradable components are closer to nature than traditional plastics as they do not emit harmful products and produce manageable

amounts of waste when decomposed by bacteria in the soil. This natural decomposition process subsequently means that the energy consumption during this process is zero and is highly cost-effective.

One of the major benefits of biodegradable products is their flexibility. After the required material is converted into a polymer, the polymer can be effortlessly integrated with the traditional components that are utilized in producing traditional plastics. There is no need for the production of completely new products to generate biodegradable plastics. Biodegradable plastic products are expected to become a flourishing industry on this generation. It is expected to make a significant impact on the export industry and in the marketing industry. China in 2016 witnessed a 13% increase in local business sales resulting from the manufacture of 290,000 tons of biodegradable plastic products.^[108] It is also stated that the country only used 130,000 tons of the manufactured products but accounted for an increase in sales of \$350 million. As the awareness and willingness to reduce carbon footprint increases, it can be strongly anticipated that biodegradable plastic products will see a surge in demand very soon. Many companies such as Coca-Cola have already proceeded to target this area of awareness by marketing bottles made from biodegradable plastics.^[109] This not only increases their company sales with this marketing strategy but also positively helps the environment. These strategies can potentially be utilized in industries associated with polymeric fiber applications to positively impact its business. Another desirable quality of biodegradable plastics is its ability to decompose under certain desired conditions. For instance, corn starch which is a significant ingredient used in the manufacture of biodegradable plastics, can be easily broken down when in contact with water in a matter of weeks.^[110]

Regardless of the many benefits of using biodegradable plastics over traditional plastics, there are multiple disadvantages that need to be taken into consideration. Biodegradable plastics are produced from natural materials such as soybean and corn. However, there are potential risks of contamination via pesticides, which can be easily conveyed to the end product. Another drawback of biodegradable plastics is the requirement for expensive industrial processors and composters, mainly those that need high industrial-magnitude temperatures to be broken down.^[111] The availability of equipment may also cause issues. Furthermore, it is an obstacle to distinguish between biodegradable and non-biodegradable polymers, as they should not be assorted when discarded. This would result in bioplastics being contaminated, which subsequently means that they cannot be easily recyclable and add up to the waste volume.^[112] Methane is produced from some biodegradable polymer during decomposition in landfills. Methane is 84 times more potent than CO₂ and also absorbs heat faster which significantly drives climate change.^[112] Biodegradable polymers do not decompose in ocean waters due to the overall cold temperature of ocean waters. Sufficient manufacture of biodegradable plastics will need the use of cropland to supply material instead of growing food. With food shortage and hunger striking 1 in 5 families in developed countries and significantly more in developing regions, there is an ethical debate on the justification to expand this industry.^[114] At present, it costs around 20–50% to manufacture bioplastic in comparison to regular plastics.^[115] However, with the implementation of new technology which is currently being researched like the pressurized

gyration system for the manufacture of polymeric fibers, these costs can be seriously reduced. Some biodegradable plastic products are known to contain certain metals, which may evolve during decomposition.^[7] For instance, high quantities of cobalt and lead in a certain brand of biodegradable plastic bag, which raises the question about its potential toxicity during decomposition. Regardless of the fact that biodegradable polymers can effortlessly decompose quickly, these materials require to follow a very specific disposal method without exception as the process can be hindered. Disposing these plastics directly into a landfill will produce methane and it is essential to verify they are recycled or that other waste reduction procedures are met. Water is necessary for the timely decomposition of biodegradable polymers made using corn starch.^[116] Rain can easily support decomposition. However, issues arise when there is no rain present and managing waste during such instances. In spite of recent achievements, the economic feasibility of composting plastic waste in conventional waste facilities is still some distance away. It is also noteworthy that biodegradable polymers in general are functionally second to traditional polymers. There is a requirement to move consumer behavior to incomputerate and accept less durable biodegradable plastic products, which will eventually lower the commencement of biodegradable polymers being a commercial reality.^[117] There have been rising concerns over greenwashing within industries, where the UK government is aiming to develop standards for bioplastics and biodegradable plastics to curb this.^[118] However, regulations that are more stringent are also essential on a global scale to set high threshold standards for sustainability.^[119]

6.2. Green Polymeric Fiber Production Methods

The use of nanotechnology methods and materials has been proven to pose some damage to the environment. However, it can also be argued that the use of these methods and materials has also positively reflected on the environment. For instance, pollution of ground and surface water around the globe is now a significant problem. Regardless of the environmental effects of most of the fiber production methods, nanotechnology has considerably progressed water treatment development.^[54] Material selection plays a very crucial role in the design and manufacture of sustainable, ecofriendly products in the field of engineering design.^[120] Materials are utilized to make use of their physical and mechanical properties depending on the application of the product. Polymer composite materials are an example of this, for instance it provides ease of manufacture, productivity and is cost effective.^[121] Composites are bespoke materials where it possesses distinctive attributes, thus properties can be changed by altering the reinforcement and matrix phase.^[122] In comparison to synthetic fibers, natural fibers can be advantageous due to their availability and abundance, along with their cost effectiveness.^[123] These fibers have been introduced to composites in place of synthetic fibers to make composites lighter.

The use of work-related nanomaterials is managed by the Control of Substances Hazardous to Health (COSHH). COSHH is a law that is requisite of employers to control substances that are hazardous to health, which also includes nanomaterials and solvents.^[124] In the USA, the Toxic Substance Control Act, curtails the use of chemical substances that present unreasonable

dangers to human health and the environment.^[125] To keep up with this, manufacturing methodologies have progressed to adhere to these regulations. For instance, this is reflected in the textile industry where firms have taken on ecofriendly manufacturing and management techniques, such as greener fabrication processes, circular supply chains and recycling. It is also shown in the automotive industry where vehicle emissions are controlled by regulations along with new technologies such as hybrids and electric vehicles. However, in comparison the biomaterials and medical devices industry where the application of polymeric fibers has advanced significantly, greener polymeric nanofiber production practices remain nascent.^[48]

6.3. Hollow Fibers

Polymeric hollow fibers are currently being researched, where it is mostly focused on its use on membrane technology and spun for applications in desalination, gas separation, artificial organs, and water treatment. This is due to the highly sizeable area-to-volume ratio hollow fibers offer, which permits compactness. Hollow fibers are mostly produced using phase separation techniques.^[126] However, this has also been achieved using other methods such as electrospinning in the submicrometer scale. From an environmental standpoint, polymeric hollow fibers consist of less polymers in comparison to regular polymeric fibers of the same outer diameter and also offer the same properties of regular fibers. However, there may be a bit of compromise in terms of its mechanical strength from radial stresses. There is potential to produce hollow fibers with multiple thin sheaths, which may possibly structurally reinforce the fiber. The bicomponent (or multi-component) structure of these multisheath nanotubes will subsequently provide added physical, mechanical and chemical features as a result of combining multiple polymers. Polymeric hollow submicrometer fibers are relatively new in comparison to “regular” submicrometer fibers and therefore may have possible undocumented problems. Depending on the application of hollow polymeric fibers, fouling can be a major concern especially in membrane-related applications.^[127] Regardless of these concerns, hollow fibers have great potential in providing a sustainable solution to curbing environmental effects in comparison to the use of solid polymeric fibers throughout the phases of its life cycle. This is mainly due to hollow fibers requiring less polymers in comparison to solid fibers of the same diameter.

6.4. Sustainable Polymers and Solvents

Natural polymers also known as biopolymers may also be another potential solution in controlling the environmental effects from polymeric fibers production. They have already been utilized in a diverse range of biomedical applications such as in tissue engineering and pharmaceuticals.^[128] These polymers offer a significant contribution in curtailing the need for fossil fuels, which subsequently reduces carbon dioxide emissions. Natural polymers occur naturally or are produced by living organisms. Although, there is usually a requirement for these naturally occurring materials to be processed to obtain natural polymers and their mediocre transformation into polymers is yet a significant

challenge.^[129] It was previously mentioned that polymeric fiber manufacture is only just recently seeing some research focused on how to make the processes greener. However, green chemistry supported by green engineering has been seeking to improve efficiency and reduce health and environmental effects throughout the chemical manufacturing process.^[130] Green polymers, on the other hand, are manufactured utilizing green chemistry, which takes into consideration the sustainability of the entire process to produce the final polymer product. Natural polymers are not necessarily green polymers. A few principles the production process of green polymers encompasses are wasteless manufacture processes, along with a high content of raw material, low carbon footprint, high-energy efficiency, and the use of renewable energy. In recent times, PEO has shown a lot of attention due to its nonvolatility and very low toxicities.^[131] They are currently in use in many pharmaceutical and cosmetic applications. Food chemistry and food processing are known to be ample sources to generate ideas on how to use renewable sources and apply green chemistry to create environmentally friendly polymers.^[132] Regardless, synthetic polymers such as PEO are still commonly utilized over natural polymers as they are functionally superior. The use of such low toxic synthetic polymers can still be more environmentally beneficial in comparison to other synthetic polymers due to features such as water solubility. Similarly, fiber production from water-soluble cyclodextrin has also recently been successful and the use of such oligosaccharide polymeric fibers in a variety of functional applications such as in healthcare can enhance suitability goals.^[133]

Green solvents are a substitute for organic solvents. Organic solvents are classed as synthetic or natural, whereas similar to natural polymers, natural solvents are derived from living organisms. The global biobased chemical market is growing in size and importance. Biobased solvents such as glycerol and 2-methyltetrahydrofuran are often discussed as important introductions to the conventional repertoire of solvents.^[24] One of the primary aims of green chemistry is the use of renewable sources over nonrenewable feedstock.^[107] Bio-based solvents are considered green solvents as they take green chemistry into consideration as they are generally derived from agricultural crops. Green solvents help in contributing to making a chemical reaction green, to support green chemistry.^[134] Green solvents are safe, generally biodegradable and very low in toxicity, throughout their production to their final product. Water is the greenest solvent taking into consideration the principles of green chemistry.^[135] However, the use of a non-green polymer would cancel out the environmental benefits of this solvent in the production of polymeric fibers. Healthcare industry giants such as Pfizer and GSK have adapted the use of green chemistry when making solvent selections in the recent past.^[136] The use of very low toxic solvents or zero toxic solvents such as water is ideal for medical applications due to minimal hazards to humans. It is highly important that there is a strong focus on green chemistry in the making of polymeric fibers to further support the confidence in large-scale production and use in industries.

7. Concluding Remarks

As the friction between sustainable development and environmental protection is increasingly becoming more significant,

researchers are starting to rigorously consider green chemistry in the production of polymeric fibers. There is a need to find solutions from “cradle to grave,” to effectively combat all negative environmental effects from the application of polymeric fibers. The pros and cons of the use of bioplastics or biodegradable polymers suggest that the best solution is to avoid or reduce using polymers. This is regardless of the materials the polymers are produced from and it seems to be the only real way to curb pollution and waste. However, the functionality and versatility of polymers seemed to have outweighed environmental concerns in the past. A potential solution is the use of polymeric hollow fibers which can be suitable for multiple applications. The making of hollow polymeric fibers with the use of green polymers and green solvents in an energy-efficient process such as pressurized gyration may potentially be a very promising route for the mass-production of the greenest polymeric fibers. The use of a green solvent will also negate the drawback of the use of solvents in methods that require solvents to produce polymeric fibers. It is also critically important that more stringent global regulations are drawn to control polymer recycling and end of life. It is clear that current technologies are not all the way there yet in terms of fully sustainable polymeric fiber manufacture, however, where there are technological obstacles there is also scope for creativity and innovation.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

energy consumption, environmental impacts, manufacturing, polymeric fibers, sustainability

Received: May 30, 2022

Revised: August 25, 2022

Published online: October 19, 2022

- [1] J. K.-H. Hui, M. J. MacLachlan, *Coord. Chem. Rev.* **2010**, 254, 2363.
- [2] J. Egan, S. Salmon, *SN Appl. Sci.* **2021**, 4, 22.
- [3] P. J. J. Francis, *Curr. Trends Biomed. Eng. Biosci.* **2018**, 15, 1.
- [4] A. Chamas, H. Moon, J. Zheng, Y. Qiu, T. Tabassum, J. Jang, M. Abu-Omar, S. L. Scott, S. Suh, *ACS Sustainable Chem. Eng.* **2020**, 8, 3494.
- [5] Z. Rathnayake, ‘Nurdles are everywhere’, how plastic pellets ravaged a Sri Lankan paradise [Internet]. the Guardian. <http://www.theguardian.com/environment/2022/jan/25/nurdles-are-everywhere-how-plastic-pellets-ravaged-a-sri-lankan-paradise> (accessed: March 2022).
- [6] S. Smith, Oil, acid, plastic, Inside the shipping disaster gripping Sri Lanka [Internet]. UNEP. <http://www.unep.org/news-and-stories/story/oil-acid-plastic-inside-shipping-disaster-gripping-sri-lanka> (accessed: January 2022).
- [7] J. H. Song, R. J. Murphy, R. Narayan, G. B. H. Davies, *Philos. Trans. R. Soc., B* **2009**, 364, 2127.
- [8] J. Brizga, K. Hubacek, K. Feng, *One Earth* **2020**, 3, 45.
- [9] Kenry, C. T. Lim, *Prog. Polym. Sci.* **2017**, 70, 1.
- [10] F. Thevenon, C. Carroll, J. Sousa, *Gland* **2014**, 52.
- [11] L. Hamilton, S. Feit, The Hidden Costs of a Plastic Planet [Internet]. Centre for International Environmental Law. <http://www.ciel.org/wp-content/uploads/2019/05/Plastic-and-Climate-FINAL-2019.pdf> (accessed: May 2022).
- [12] S. Laville, Single-use plastics a serious climate change hazard, study warns [Internet]. the Guardian. <http://www.theguardian.com/environment/2019/may/15/single-use-plastics-a-serious-climate-change-hazard-study-warns> (accessed: January 2019).
- [13] L. Parker, A whopping 91% of plastic isn't recycled [Internet]. National Geographic. <http://www.nationalgeographic.com/science/article/plastic-produced-recycling-waste-ocean-trash-debris-environment> (accessed: January 2022).
- [14] World Economic Forum, Ellen MacArthur Foundation and McKinsey & Company. The New Plastics Economy [Internet]. Ellen MacArthur Foundation, <http://ellenmacarthurfoundation.org/the-new-plastics-economy-rethinking-the-future-of-plastics> (accessed: January 2022).
- [15] L. Fernández, Chemical fiber global production by type 2020 | Statista [Internet]. Statista. <http://www.statista.com/statistics/271651/global-production-of-the-chemical-fiber-industry/> (accessed: May 2022).
- [16] E. MacGregor, in *Encyclopedia of Physical Science and Technology*, (Ed.: R. A. Meyers), Academic Press, Diego, CA **2003**, p. 207.
- [17] P. Baheti, A Simple Step-By-Step Explanation [Internet]. British Plastics Federation. <http://www.bpf.co.uk/plastipedia/how-is-plastic-made.aspx> (accessed: January 2022).
- [18] I. M. Hutten, in *Handbook of Nonwoven Filter Media* (Ed.: I. M. Hutten), Elsevier, Amsterdam **2007**, p. 103.
- [19] L. Zhao, W. Zhu, M. I. Papadaki, M. S. Mannan, M. Akbulut, *ACS Omega* **2019**, 4, 8136.
- [20] M. Ramesh, K. Palanikumar, K. H. Reddy, *Renewable Sustainable Energy Rev.* **2017**, 79, 558.
- [21] J. N. Hahladakis, C. A. Velis, R. Weber, E. Iacovidou, P. Purnell, *J. Hazard. Mater.* **2018**, 344, 179.
- [22] I. Alghoraibi, S. Alomari, in *Handbook of Nanofibers* (Eds: A. Barhoum, M. Bechelany, A. S. H. Makhlof), Springer Nature, Cham, Switzerland **2018**, p. 1.
- [23] J. Mancuso, Three Types of Solvents for Industrial Cleaning [Internet]. Ecolink.com. 2015 <http://ecolink.com/info/types-of-solvents/> (accessed: January 2022).
- [24] J. Clark, T. Farmer, A. Hunt, J. Sherwood, *Int. J. Mol. Sci.* **2015**, 16, 17101.
- [25] D. R. Joshi, N. Adhikari, *J. Pharm. Res. Int.* **2019**, 28, 1.
- [26] J. A. Bonventre, in *Encyclopedia of Toxicology*, Elsevier, Amsterdam **2014**, p. 356.
- [27] J. Firestone, S. Gospe, in *Clinical Neurotoxicology*, Elsevier, Amsterdam **2009**, p. 401.
- [28] I. Smallwood, *Handbook of Organic Solvent Properties*, Butterworth-Heinemann, Oxford, UK **2012**.
- [29] G. Buschle-Diller, J. Cooper, Z. Xie, Y.e Wu, J. Waldrup, X. Ren, *Celulose* **2007**, 14, 553.
- [30] C. D. Klaassen, L. J. Casarett, *Casarett and Doull's Toxicology: The Basic Science of Poisons*, McGraw-Hill Publishing, Blacklick, OH **2013**.
- [31] R. V. Branchflower, D. S. Nunn, R. J. Highet, J. H. Smith, J. B. Hook, L. R. Pohl, *Toxicol. Appl. Pharmacol.* **1984**, 72, 159.
- [32] R. Reitz, Ann. Ist. Super. Sanita [Internet]. 1991 [http://pubmed.ncbi.nlm.nih.gov/1820733/#,~,text=Dichloromethane%20\(methylene%20chloride%2C%20CH2Cl2\),majority%20of%20their%20natural%20lifetime](http://pubmed.ncbi.nlm.nih.gov/1820733/#,~,text=Dichloromethane%20(methylene%20chloride%2C%20CH2Cl2),majority%20of%20their%20natural%20lifetime) (accessed: March 2022).
- [33] C. Vitale, S. Gutovitz, *Aromatic Toxicity*, StatPearls Publishing, Treasure Island, FL **2021**.
- [34] J. K. Dunnick, A. R. Pandiri, B. A. Merrick, G. E. Kissling, H. Cunny, E. Mutlu, S. Waidyanatha, R. Sills, H. L. Hong, T.v. Ton, T. Maynor, L. Recio, S. L. Phillips, M. J. Devito, A. Brix, *Toxicol. Rep.* **2018**, 5, 615.

- [35] R. I. Ehrlich, D. C. S. Woolf, D. A. Kibel, *Occup. Med.* **2011**, 62, 64.
- [36] F. D. Dick, *Occup. Environ. Med.* **2006**, 63, 221.
- [37] A. Nicolae, A. Grumezescu, in *Materials for Biomedical Engineering* (Eds: V. Grumezescu, A. M. Grumezescu), Elsevier, Amsterdam **2019**, p. 1.
- [38] J. Xue, T. Wu, Y. Dai, X. Y. Electrospinning, E. Nanofibers, *Chem. Rev.* **2019**, 119, 5298.
- [39] Y. Engel, J. Schiffman, J. Goddard, V. Rotello, *Mater. Today* **2012**, 15, 478.
- [40] M. d. Pervez, G. Stylios, *Nanomaterials* **2018**, 8, 383.
- [41] W. Teo, Benign and green electrospinning [Internet]. Electrospintech.com. **2016**, <http://electrospintech.com/greenelectrospinning.html#.YfaHvvvP1D8> (accessed: January 2022).
- [42] C. Sudhakar, N. Upadhyay, A. Jain, A. Verma, R. Narayana Charyulu, S. Jain, in *Nanotechnology Applications for Tissue Engineering*, (Eds: S. Thomas, Y. Grohens, N. Ninan), Elsevier, Amsterdam **2015**, p. 77.
- [43] A. Kusumaatmaja, B. Sukandaru, T. K. Chotimah, *AIP Conf. Proc.* **2016**, 1755, 150006.
- [44] M. Chai, W. Tong, Z. Wang, S. Zhao, Y. Zhang, *Macromol. Mater. Eng.* **2021**, 307, 2100753.
- [45] S. Seif, F. Graef, S. Gordon, M. Windbergs, *Dissolution Technol.* **2016**, 23, 6.
- [46] T. D. Brown, P. D. Dalton, D. W. Hutmacher, *Prog. Polym. Sci.* **2016**, 56, 116.
- [47] M. Bubakir, H. Li, A. Barhoum, *Handbook of Nanofibers, Advances in Melt Electrospinning Technique*, 1st ed., Springer, Berlin **2019**.
- [48] C. Z. Mosher, P. A. P. Brudnicki, Z. Gong, H. R. Childs, S. W. Lee, R. M. Antrobus, E. C. Fang, T. N. Schiros, H. H. Lu, *Biofabrication* **2021**, 13, 035049.
- [49] International Council for Harmonisation. Impurities, Guideline for Residual Solvents Q3C(R8) [Internet]. p. 11. http://database.ich.org/sites/default/files/Q3C-R8_Guideline_Step4_2021_0422_1.pdf (accessed: 2021).
- [50] Scientific Laboratory Supplies Ltd. MIX5000 [Internet]. <http://www.scientificlabs.co.uk> <http://www.scientificlabs.co.uk/product/MIX5000> (accessed: March 2022).
- [51] H. Apparatus, PHD 4400 Syringe Pump Series User's Manual [Internet]. Harvardapparatus.com. **2001**, http://www.harvardapparatus.com/media/harvard/pdf/702200_Syringe%20Pump_PHD_4400_Manual.pdf (accessed: February 2022).
- [52] M. Inc, High Voltage Power Supply | EPR series | Matsusada Precision [Internet]. Matsusada Precision. **2022**, <http://www.matsusada.com/product/hvps1/handy/epr/> (accessed: March 2022).
- [53] T. Chung, Y. Feng, *Hollow Fiber Membranes, Fabrication and Applications*, Elsevier, Amsterdam **2021**.
- [54] J. F. Kim, J. i H. Kim, Y. M. Lee, E. Drioli, *AIChE J.* **2015**, 62, 461.
- [55] D. Bahadur Pal, D. Dayal Giri, in *Nanofibers – Synthesis, Properties and Applications*, (Ed: B. Kumar) IntechOpen, London **2021**, p. 4.
- [56] G. Conoscenti, V. Carrubba, V. Brucato, *Arch. Chem. Res.* **2017**, 1.
- [57] X. Dong, D. Lu, T. A. L. Harris, I. C. Escobar, *Membranes* **2021**, 11, 309.
- [58] X. Zhang, Y. Lu, *Polym. Rev.* **2014**, 54, 677.
- [59] S. Gay, G. Lefebvre, M. Bonnin, B. Nottelet, F. Boury, A. Gibaud, B. Calvignac, *J. Supercrit. Fluids* **2018**, 136, 123.
- [60] T. Pella, Inc. Hot Plate, Magnetic Stirrer, Benchmark [Internet]. Tedpella.com. **2022**. http://www.tedpella.com/histo_html/hotplate.aspx (accessed: February 2022).
- [61] M. Farley, B. McTeir, A. Arnott, A. Evans, [Internet]. The University of Edinburgh Social Responsibility & Sustainability, 2015 p. 5. http://www.ed.ac.uk/files/atoms/files/efficient_ult_freezer_storage.pdf (accessed: February 2022).
- [62] R. McCarthy, How Much Power a Fridge Uses – in Watts, Cost & kWh [Internet]. Reduction Revolution. **2019**, <http://reductionrevolution.com.au/blogs/how-to/fridge-power-consumption> (accessed: February 2022).
- [63] M. Roy, High-Performance Diaphragm Pump | Megaroyal | Milton Roy [Internet]. Miltonroy.com. **2022**, <http://www.miltonroy.com/en-gb/process-pumps/megaroyal-diaphragm-process-pump> (accessed: February 2022).
- [64] Z. Yang, B. Xu, *J. Mater. Chem.* **2007**, 17, 2385.
- [65] A. Bezryadin, R. M. Westervelt, M. Tinkham, *Appl. Phys. Lett.* **1999**, 74, 2699.
- [66] H.-W. Liang, Q.-F. Guan, Li-F. Chen, Z. Zhu, W.-. J. Zhang, S.-H. Yu, *Angew. Chem., Int. Ed.* **2012**, 51, 5101.
- [67] L. Feng, S. Li, H. Li, J. Zhai, Y. Song, L. Jiang, D. Zhu, *Angew. Chem., Int. Ed.* **2002**, 41, 1221.
- [68] Amazon. Nordstrand 90 W Hot and Cold Water 1 Bar Pressure Booster Pump [Internet]. Amazon.co.uk. **2022**, http://www.amazon.co.uk/Nordstrand-Cold-Water-Pressure-Booster/dp/B01CO2WLJO/ref=asc_df_B01CO2WLJO/?tag=googshopuk-21&linkCode=df0&hvadid=231845867220&hvpos=&hvnetw=g&hvrand=6746337029626611829&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9045997&hvtargid=pla-421666631245&psc=1 (accessed: February 2022).
- [69] V. Beachley, X. Wen, *Prog. Polym. Sci.* **2010**, 35, 868.
- [70] D. Lucas, M. Lacarin, "DRAWING"- THE PRODUCTION OF INDIVIDUAL NANOFIBERS BY EXPERIMENTAL METHOD. [Internet]. **2011**, [cited 18 April 2022]. <http://www.semanticscholar.org/paper/%22DRAWING%22-THE-PRODUCTION-OF-INDIVIDUAL-NANOFIBERS-Lukas-Lacarin/d0a69e873c2a4e4f96a673b40b7eff123eece688# citing-papers> (accessed: April 2022).
- [71] Amazon. [Internet]. Amazon.co.uk. **2022**, <http://www.amazon.co.uk/INTLLAB-Magnetic-Stainless-Stirring-Capacity/dp/B072K24X5P#descriptionAndDetails> (accessed: March 2022).
- [72] A. Saheed, Thesis for M.Eng., University College London, **2020**.
- [73] P. L. Heseltine, J. Ahmed, M. Edirisinghe, *Macromol. Mater. Eng.* **2018**, 303, 1800218.
- [74] H. Alenezi, M. E. Cam, M. Edirisinghe, *Appl. Phys. Rev.* **2019**, 6, 041401.
- [75] RS Components, L., RS PRO Geared DC Motor, 21.2 W, 4.5 → 15 V, 154.4 gcm, 13360 rpm, 3.18 mm Shaft Diameter | RS Components [Internet]. Uk.rs-online.com. <http://uk.rs-online.com/web/p/dc-motors/2389759> (July 2022). (accessed: July 2022).
- [76] S. Mahalingam, S. Homer-Vanniasinkam, M. Edirisinghe, *Mater. Des.* **2019**, 178, 107846.
- [77] S. Evans, J. Gabbatiss, R. McSweeney, A. Chandrasekhar, A. Tandon, G. Viglione, Z. Hausfather, X. You, J. Goodman, S. Hayes, COP26, Key outcomes agreed at the UN climate talks in Glasgow – Carbon Brief [Internet]. Carbon Brief. **2021**, <http://www.carbonbrief.org/cop26-key-outcomes-agreed-at-the-un-climate-talks-in-glasgow> (accessed: January 2022).
- [78] B. Ksapabutr, M. Panapoy, in *Metal Oxide-Based Nanofibers and Their Applications*, (Eds: V. Esposito, D. Marani), Elsevier, Amsterdam **2022**, p. 3.
- [79] S. Mahalingam, S. Huo, S. Homer-Vanniasinkam, M. Edirisinghe, *Polymers* **2020**, 12, 1709.
- [80] J. Ahmed, R. K. Matharu, T. Shams, U. E. Illangakoon, M. Edirisinghe, *Macromol. Mater. Eng.* **2018**, 303, 1700577.
- [81] M. Ghalia, Y. Dahman, in *Nanobiomaterials in Soft Tissue Engineering*, (Ed: A. Grumezescu), Elsevier, Amsterdam **2016**, p. 141.
- [82] S. Nune, K. Rama, V. Dirisala, M. Chavali, in *Nanostructures for Novel Therapy*, (Eds: D. Fikai, A. M. Grumezescu), Elsevier, Amsterdam **2017**, p. 281.
- [83] S. Mahalingam, M. Edirisinghe, *Macromol. Rapid Commun.* **2013**, 34, 1134.

- [84] F. G. Calvo-Flores, M. J. Monteagudo-Arrebola, J. A. Dobado, J. Isac-García, *Top. Curr. Chem.* **2018**, 376, 18.
- [85] H. Cao, X. Wang, *SusMat* **2021**, 1, 88.
- [86] M. Kemmere, in *Supercritical Carbon Dioxide: in Polymer Reaction Engineering*, (Eds: M. F. Kemmere, T. Meyer), Wiley VCH, Weinheim, **2006**, p. 1.
- [87] P. Froehlich, A Sustainable Approach to the Supply of Nitrogen. Parker Balston [Internet]. **2013**, <http://www.parker.com/literature/Balston%20Filter/IND/IND%20Technical%20Articles/PDFs/Sustainable%20Approach%20to%20N2%20Supply.pdf> (accessed: January 2022).
- [88] E. Yurday, Average Cost of Electricity per kWh in the UK 2022 [Internet]. Nimbalefins.co.uk. **2022**, <http://www.nimbalefins.co.uk/average-cost-electricity-kwh-uk> (accessed: March 2022).
- [89] S. Brown, Gas prices to add £29 bn to UK electricity bills [Internet]. Ember. **2021**, <http://ember-climate.org/insights/research/gas-price-spike-to-add-29-billion-to-uk-electricity-bills-next-year> (accessed: March 2022).
- [90] Department for Business, Energy & Industrial Strategy. UK energy in brief 2021. National Statistics, **2021**, p. 28.
- [91] A. Vaughan, Biodegradable plastic ‘false solution’ for ocean waste problem [Internet]. the Guardian. **2016**, <http://www.theguardian.com/environment/2016/may/23/biodegradable-plastic-false-solution-for-ocean-waste-problem> (accessed: January 2022).
- [92] I. D. Posen, P. Jaramillo, A. E. Landis, W. M. Griffin, *Environ. Res. Lett.* **2017**, 12, 034024.
- [93] R. Cho, The truth about bioplastics [Internet]. Phys.org. **2017**, <http://phys.org/news/2017-12-truth-bioplastics.html> (accessed: January 2022).
- [94] F. Asghari, M. Samiei, K. Adibkia, A. Akbarzadeh, S. Davaran, *Artif. Cells, Nanomed., Biotechnol.* **2016**, 45, 185.
- [95] M. Tabone, J. Cregg, E. Beckman, A. Landis, *Environ. Sci. Technol.* **2010**, 44, 8264.
- [96] C. Goodall, Bioplastics, an important component of global sustainability [Internet]. Carbon Commentary. **2011**, <http://www.carboncommentary.com/blog/2011/09/02/bioplastics-an-important-component-of-global-sustainability> (accessed: January 2022).
- [97] G. Haut, M. Bolger, D. Alvarès, M. Blondeau, C. Wachholz, *Bioplastics in a Circular Economy, The need to focus on waste reduction and prevention to avoid false solutions*, [Internet]. Surfrider Foundation Europe, Friends of the Earth Europe, Zero Waste Europe, ECOS, and European Environmental Bureau., **2017**, http://zerowasteurope.eu/wp-content/uploads/2019/11/zero_waste_europe_joint_position_paper_bioplastics_in_CE_the_need_to_focus_on_waste_reduction_prevention_to_avoid_false_solutions.pdf (accessed: February 2022).
- [98] G. Atiwesh, A. Mikhael, C. C. Parrish, J. Banoub, T.-A. T. Le, *Heliyon* **2021**, 7, e07918.
- [99] British Plastics Federation. Oil Consumption [Internet]. British Plastics Federation. **2019**, http://www.bpf.co.uk/press/oil_consumption.aspx (accessed: January 2022)
- [100] Y. Xu, L. Lin, M. Xiao, S. Wang, A. T. Smith, L. Sun, Y. Meng, *Prog. Polym. Sci.* **2018**, 80, 163.
- [101] S. Gibbins, [Internet]. *Environment* **2018**, <http://www.nationalgeographic.com/environment/article/are-bioplastics-made-from-plants-better-for-environment-ocean-plastic> (accessed: January 2022).
- [102] R. Mathers, M. Meier, *Green Polymerization Methods: Renewable Starting Materials, Catalysis and Waste Reduction*, Wiley-VCH, Weinheim **2011**.
- [103] H. Ritchie, M. Roser, Plastic Pollution [Internet]. Our World in Data. **2018**, <http://ourworldindata.org/plastic-pollution> (accessed: January 2022).
- [104] J. Rohrer, Plastic bags and plastic bottles – CO2 emissions during their lifetime – Time for Change [Internet]. Time for Change. **2022**, <http://timeforchange.org/plastic-bags-and-plastic-bottles-co2-emissions-during-their-lifetime/> (accessed: January 2022).
- [105] L. Cabernard, S. Pfister, C. Oberschelp, S. Hellweg, *Nat. Sustainability* **2022**, 5, 139.
- [106] B. S. Rubin, *J. Steroid Biochem. Mol. Biol.* **2011**, 127, 27.
- [107] M. A. Dubé, S. Salehpour, *Macromol. React. Eng.* **2013**, 8, 7.
- [108] L. Wood, 2017 Assessment of China’s Market for Biodegradable Plastics [Internet]. Global Newswire. **2017**, http://www.researchandmarkets.com/research/br4smv/assessment_of (accessed: January 2022)
- [109] A. Barrett, V. Barrett Coca-Cola Goes Bioplastics [Internet]. Bioplastics, Chemical Recycling, Ocean Plastic, Microplastic, Carbon. 2019, <http://bioplasticsnews.com/2019/08/15/coca-cola-goes-bioplastics/> (accessed: January 2022).
- [110] Y. Achlim, The Pros and Cons of Corn Plastic [Internet]. One Green Planet. **2021**, <http://www.onegreenplanet.org/environment/the-pros-and-cons-of-corn-plastic/> (accessed: January 2022).
- [111] Department for Business, Energy & Industrial Strategy and Department for Environment, Food & Rural Affairs. *Standards for bio-based, biodegradable, and compostable plastics. HM Government, 2021*, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/976912/standards-bio-based-biodegradable-compostable-plastics.pdf (accessed: July 2022).
- [112] European Environment Agency. Biodegradable and compostable plastics—challenges and opportunities [Internet]. European Environment Agency. **2020**, <http://www.eea.europa.eu/publications/biodegradable-and-compostable-plastics> (accessed: July 2022).
- [113] D. T. Shindell, G. Faluvegi, D. M. Koch, G. A. Schmidt, N. Unger, S. E. Bauer, *Science* **2009**, 326, 716.
- [114] C. M. Pollard, S. Booth, *Int. J. Environ. Res. Public Health* **2019**, 16, 1804.
- [115] N. I. Ibrahim, F. S. Shahar, M. T. H. Sultan, A. U. M. d Shah, S. N. A. Safri, M. H. Mat Yazik, *Coatings* **2021**, 11, 1423.
- [116] L. Cowley, Compostable plastic Eco World [Internet]. Eco World. 2020. <http://ecoworldonline.com/what-is-corn-starch-plastic/> (accessed: January 2022).
- [117] B. Lim, E. Thian, *Sci. Total Environ.* **2021**, 813, 151880.
- [118] V. Goel, P. Luthra, G. S. Kapur, S. S. V. Ramakumar, *J. Polym. Environ.* **2021**, 29, 3079.
- [119] G. Bhagwat, K. Gray, S. P. Wilson, S. Muniyasamy, S. G. T. Vincent, R. Bush, T. Palanisami, *J. Polym. Environ.* **2020**, 28, 3055.
- [120] Y. T. Girijappa, S. M. Rangappa, J. Parameswaranpillai, S. Siengchin, *Front. Mater.* **2019**, 6, 1.
- [121] O. Faruk, A. Bledzki, H. Fink, M. Sain, *Macromol. Mater. Eng.* **2013**, 299, 9.
- [122] M. Sanjay, B. Yogesha, *Mater. Today: Proc.* **2017**, 4, 2739.
- [123] P. Madhu, M. R. Sanjay, P. Senthamaraiannan, S. Pradeep, S. S. Saravanakumar, B. Yogesha, *J. Nat. Fibers* **2017**, 16, 25.
- [124] Health and S. Executive, Using nanomaterials at work [Internet]. Crown, **2013**, <http://www.hse.gov.uk/pubns/books/hsg272.htm> (accessed: April 2022).
- [125] C. Auer, F. Kover, J. Aidala, C. Blunck, M. Greenwood, [Internet]. EPA Alumni Association, 2020. <http://www.epaalumni.org/hcp/toxics.pdf> (accessed: April 2022).
- [126] K. Khulbe, C. Feng, T. Matsuura, M. Khayet, *J. Appl. Membr. Sci. Technol.* **2017**, 4, 54.
- [127] M. Demeuse, in *Handbook of Textile Fibre Structure* (Eds: S. J. Eichhorn, J. W. S. Hearle, M. Jaffe, T. Kikutani), Woodhead Publishing, Sawston, UK **2009**, p. 485.
- [128] B. ter Horst, N. Moiemien, L. Grover, in *Biomaterials for Skin Repair and Regeneration*, (Ed.: E. García-Gareta), Elsevier, Amsterdam **2019**, p. 151.

- [129] P. B. V. Scholten, J. Cai, R. T. Mathers, *Macromol. Rapid Commun.* **2021**, 42, 2000745.
- [130] M. J. Mulvihill, E. S. Beach, J. B. Zimmerman, P. T. Anastas, *Annu. Rev. Environ. Resour.* **2011**, 36, 271.
- [131] R. Webster, V. Elliott, B. Park, D. Walker, M. Hankin, P. Taupin, in *PEGylated Protein Drugs, Basic Science and Clinical Applications* (Ed.: F. M. Veronese), Springer, Berlin **2009**, p. 127.
- [132] C. M. Aberg, T. Chen, G. F. Payne, *J. Polym. Environ.* **2002**, 10, 77.
- [133] A. Kelly, J. Ahmed, M. Edirisinghe, *Macromol. Mater. Eng.* **2022**, 307, 2100891.
- [134] M. Doble, A. Kruthiventi, in *Green Chemistry and Engineering* (Ed.: M. Doble), Academic Press, San Diego, CA **2007**, pp. 93.
- [135] F. Zhou, Z. Hearne, C.-J. Li, in *Current Opinion in Green and Sustainable Chemistry* (Eds: M. C. Ncibi, B. Mahjoub, M. G. Freire, J. A. P. Coutinho), Elsevier, Amsterdam **18**, p. 118.
- [136] P. J. Dunn, *Chem. Soc. Rev.* **2012**, 41, 1452.



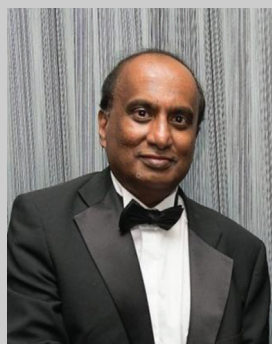
Manul Amarakoon is a doctoral researcher in the Department of Mechanical Engineering at University College London since 2021. He completed his M.Eng. undergraduate course in mechanical engineering from Oxford Brookes University UK. He further pursued an M.Sc. in engineering management at Nottingham Trent University. Manul's doctoral research is focused on the application of "green" engineering to promote sustainability in the production of submicrometer polymeric fibers.



Hussain Alenezi is a doctoral researcher in the Department of Mechanical Engineering at University College London since 2018 and is sponsored by the Kuwait government (PAAET). In 2008, he graduated with honors in his B.Eng. in mechanical engineering from Brunel University. Alenezi followed on to attain his M.Sc. in advanced mechanical engineering from Brunel University in 2010. He also accomplished his second master's degree in mechanical engineering (manufacturing, processes and automation Systems) from University College Cork in 2015. Alenezi's research focuses on designing and constructing novel gyrosinning devices for manufacturing multi-layer core-sheath polymeric fibers utilized in various healthcare applications.



Shervanthi Homer-Vanniasinkam is a consultant vascular surgeon at Leeds Teaching Hospitals NHS Trust, founding professor of surgery at the University of Warwick Medical School and professor of engineering and surgery at University College London. She has published over 160 papers and book chapters, delivered over 300 presentations and has a significant research grant portfolio. She has an outstanding track record of national and international collaborative research. She is a visiting scholar at Harvard University, the Yeoh Ghim Seng Visiting Professor of Surgery at the National University of Singapore and the Brahm Prakash Visiting Professor at the Indian Institute of Science.



Mohan Edirisinghe is Bonfield Chair of Biomaterials in UCL Mechanical Engineering. He has published over 500 journal papers. His research on materials and manufacturing for healthcare has won numerous grants and prizes, including recently, the UK Royal Academy of Engineering Prize for excellence in Materials Engineering and the Premier UK IOM3 Chapman Medal for distinguished research in Biomedical Materials. In the Queen's New Year National Honours 2021 he was appointed OBE for his services to biomedical engineering. His most recent work on innovative manufacturing of polymer fibers using pressurized gyration invented in 2013 has won 16 journal cover-papers to date.