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10 A recycling route of plastics via electrospinning: from daily wastes to functional fibers

Abstract: Since large-scale plastic production has begun in the 1940s, plastics have been produced and used globally, bringing many advantages to modern life. The consumption of plastics has increased exponentially due to their low cost, chemical resistance, lightness, durability and ability to combine with other materials. However, plastic materials represent high tonnage in urban wastes, and it is known that these plastics discarded at the end of their useful life by filling the landfill sites. Electrospinning is a well-established and versatile technique for the fabrication of submicron fibers. In addition, it is a promising approach for the recycling of waste polymers without using complex methodologies. In this chapter, utilization of electrospinning approach for the recycling of daily wastes will be discussed. The literature about the daily wastes of both synthetic materials and natural/agricultural materials will be analyzed, and the applications of these materials will be given in detail.

Keywords: antibacterial, antimicrobial, battery, biomedical, electrospinning, filtration, photocatalytic, plastic waste, polymer waste, recycling

10.1 Recycling of daily wastes and challenges

Plastics that can be described as additive-included polymers are integral part of our daily life and current industry. They are getting more interest in manufacturing due to their benefits. Figure 10.1 shows the current applications of the polymeric products: packaging (39.9%), building and construction (19.7%), automotive (8.9%), electrical and electronic (5.8%), agriculture (3.3) and others (22.4%, consumer and household goods, furniture, sports, health and safety, etc.) [1].

The production of industrial plastics dates back to the end of 1930s when Carothers and DuPont patented Nylon [2]. The global plastic production has increased exponentially during the last 50 years. Although the first production was in the middle of twentieth century all around the world, in 2015, 322 million tons of

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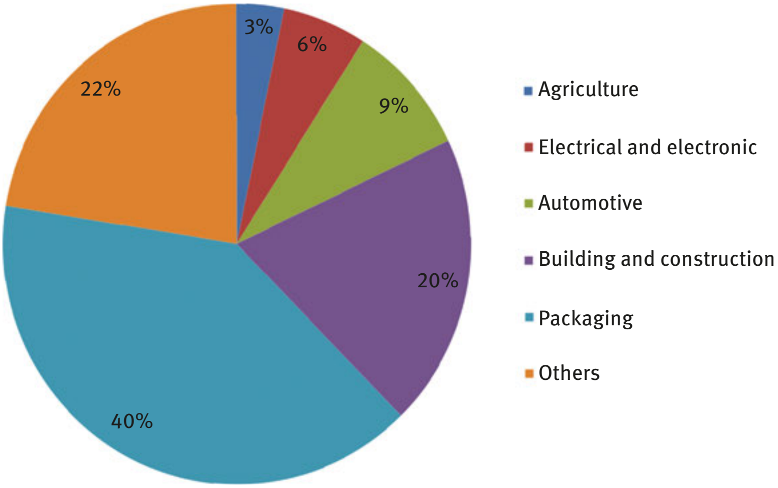


Figure 10.1: Distribution of plastic demand in Europe by 2015 (Source: Ref. [1]).

plastics were produced worldwide and this number reached to 49 million tons in Europe [1]. The synthetic plastics have replaced with glass, ceramic, wood and metal in many fields, and the commodity plastics have revolutionized the industry with the participation of polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET) and polyvinylchloride (PVC) [3]. PE could be classified into two categories: low-density PE (LDPE) and high-density PE (HDPE). While toys, pipes and several types of bottles are produced from HDPE, the raw material of softer products such as reusable bags, food packaging films and agricultural films is LDPE. Another type of commodity plastics is PP, which is used for the production of several containers, automotive parts, single-used glasses, bank notes, food packaging and hinged caps. According to the Plastics Europe Report, the production of PP reaches up to 9.2 million tons per year in 2015, and it is the most demanded polymer with 19.1%. LDPE and HDPE demands follow PP with 17.3% and 12.1%, respectively. Besides PVC, PET and PS are other much-used plastics in industry for the production of plastic cups (PS), insulation [expanded PS (EPS)], bottles (PET) and window frame (PVC) [3].(Figure 10.2) However, most of the plastic materials are not biodegradable, and degradation of these polymers takes ages in normal environmental conditions [4].

In Europe, 25.8 million tons of plastics ended up in the waste stream and only 69.2% of them was recycled or used for energy recovery according to the European reports. Postconsumer wastes can be treated with various methods such as landfilling, energy recovery and recycling in accordance with the principle of waste hierarchy [5]. Landfilling is the first option in many European countries; however, some countries apply landfill ban to achieve high recycle rates. In addition, this method must be

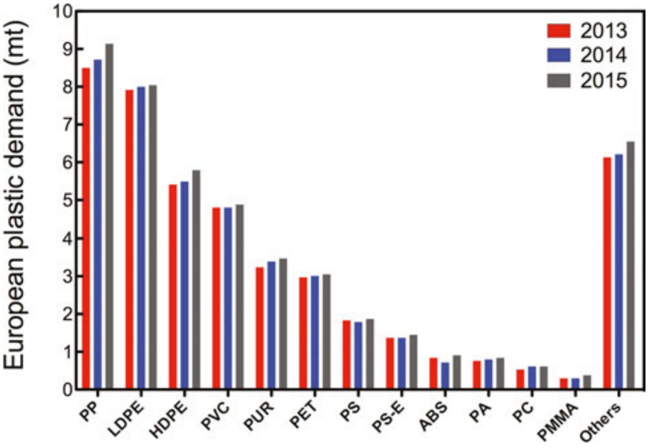


Figure 10.2: The plastic demand in Europe at 2015 including plastic materials (thermoplastics and polyurethanes) and other plastics (thermosets, adhesives, coatings and sealants). (Source: Ref. [1]).

the last choice due to requiring huge amount of space and long-term environmental problems. The use of recycled plastics is the most coherent approach among these methods. By means of recycle and reuse approach, plastics from the waste streams can be utilized in various applications instead of using virgin materials [4]. As another alternative approach to the recycling, energy recovery could be taken into account to stop the landfilling of plastics. They could be used as fuel for industrial processes, replacing fossil fuel. The energy value of plastics could be utilized for the production of electricity, heating and cooling for homes [1]. Figure 10.3 shows the change in the amounts of waste recovered, recycled and landfilled plastics in Europe (EU-28 + 2) between 2006 and 2014. The decrease in the amount of landfilled plastics from 12.9 to 8.0 million tons is the result of the increase in the recycling and energy recovery from 7.0 to 10.2 and from 4.7 to 7.7, respectively. Among all the types of wastes, packaging wastes have reached the highest recycling rate, which is around 40%, and this number represents 80% higher recycling rate than the other recycled wastes [1].

In Europe, some countries started to apply landfill ban to prompt people using another waste management methods such as energy recovery or recycling. Figure 10.4 shows the treatment percentages of postconsumer plastics in 2014. In 16 of 30 countries, the energy recovery rate is lower than the average value of 36.5%. Also, the average recycling rate was found as 27.1% and still 15 countries recycling rate is lower than this average value. Energy recovery rates are fairly high especially for the countries with landfill ban. However, the other remaining countries still prefer landfilling and even some countries do not have any energy recovery record [1].

The recycling/reprocessing approach of industrial wastes from the traditional materials has been used for many years. The similar procedure could be also

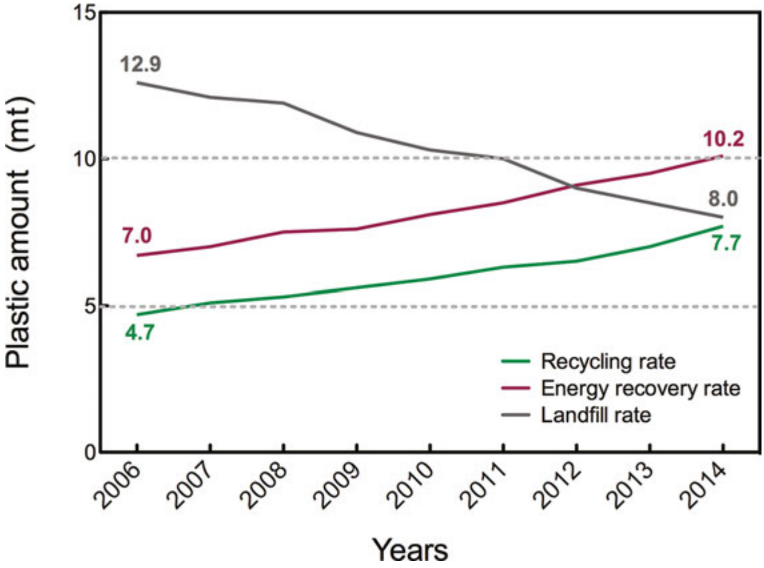


Figure 10.3: Plastic waste treatment evolution in EU-28 + 2 between 2006 and 2014 (Source: Ref. [1]).

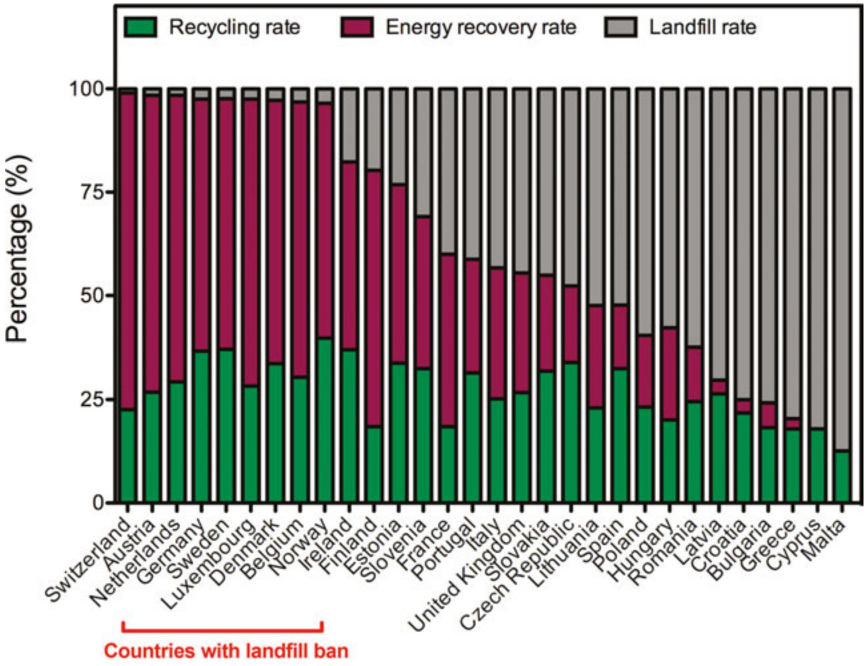
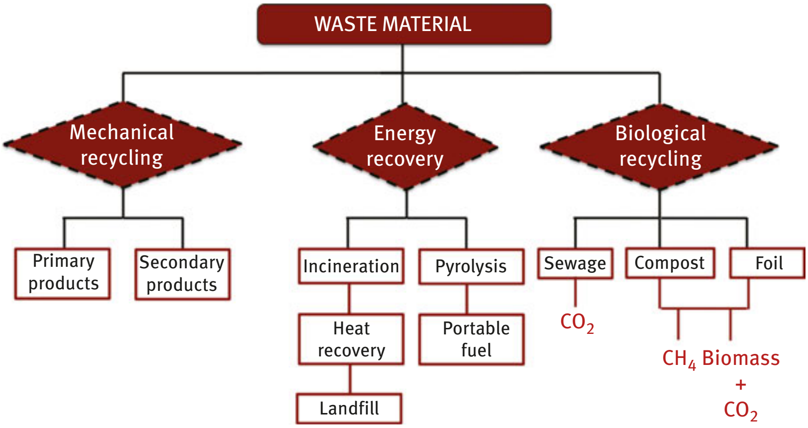


Figure 10.4: Treatment of postconsumer plastics by country in 2014 (Source: Ref. [1]).

applied to polymeric wastes to recover them for second use but there is an obstacle due to the loss of physical and mechanical properties of polymers. Because the traditional ones (i.e., glass and metal) are not organic materials, they could be recycled to secondary or tertiary products with the similar properties to primary materials. However, only the thermoplastic polymers could be recycled in this way and thermosets could not be recycled, remolded or reshaped [6]. Also, polymers lose their physical and mechanical properties after each process and final product does not have the similar properties with the raw one due to peroxidation [7–9]. Additionally, the recycling process itself uses energy and it is found that almost one third of the used energy for the production of PE is spent during its recycling. Waste plastics could be contaminated with biological residues or they could be the mixture of different materials (i.e., wood, metal or other plastics). When all the expenses (cleaning, purification, processing) for mechanical recycling are considered, the other alternatives in Scheme 10.1 could be more plausible because the ecological profits of mechanical recycling could be lost [10].



Scheme 10.1: Waste management routes (Source: Ref. [6]).

People approach with suspicion to incineration due to the emission of toxic substances to the environment. For example, polymers typically present the risk of releasing hazardous substances such as HCl from PVC, dioxins and furans from halogenated additive mixed plastics or polycyclic aromatic hydrocarbons (C_2H_2, C_2H_3, C_2H_4 and C_4H_3) from PS [11, 12]. However, incineration could be used with recovery of energy content in the plastic wastes. For local authorities, energy recovery by incineration is a preferred option because there is a financial gain by selling waste plastics as fuel due to the calorific value of some polymers is similar to fuel oil (especially for PE) [13]. Biodegradation also provides the return of nature's waste to carbon cycle, and biomass formation is an environmentally friendly approach.

However, the commodity polymers, which are currently used in industry, are not biodegradable because of the antioxidants and researches now focus on the development of polymeric materials that suit industrial requirements and return to biological cycle after their usage. Biological recycling of polymers occurs in two steps: first one is the biotic or abiotic hydrolysis and bioassimilation of biopolymer, and second one is peroxidation and bioassimilation. Because biodegradation is both an energetically and economically favorable method, it could be an alternative approach for agricultural plastics or modified synthetic plastics, which can be returned to biological cycle, to the current recycling methods [6].

10.2 Recyclable polymer wastes by electrospinning

There are visible economic and environmental consequences of plastic solid wastes due to the increasing levels of global plastic pollution both on land and in the oceans. If the plastic production continues in this direction, the current problems will be doubled in the following two decades [14]. The current task in public and private sectors is “to stay the plastics in economy and out of the oceans” [15]. Apart from the traditional methods, electrospinning method has started to be applied for the recycling of plastic materials and production of secondary materials. Thus, plastic nanofiber production from wastes could be a potentially value-added process. Synthetic plastics are dominant pollutants to the environment due to their long degradation time and abundant plastic wastes (i.e., PET, PS, PP and PVC) could be easily processed by electrospinning. On the other hand, there is a growing interest in the bio-based materials to produce economic and environmentally sustainable materials for large-scale uses. Also this type of materials represents a significant feature that they could be easily processed due to their renewability. The aim of this section is to focus on the applications of recyclable wastes from both synthetic and agricultural/natural sources in the literature.

10.2.1 Filtration and adsorption applications

Due to the growing and urbanization, water resources are rapidly contaminated with heavy metals, dyes, oil and other hazardous chemicals. Adsorption and filtration methods are widely applied processes for water and wastewater treatment, and this type of materials have been used in different forms such as beads, granules, powders, fibers and flakes [16]. There are several studies in the literature that process polymer wastes by electrospinning and fabricate recycled filtration membranes or adsorbents.

Water bottles are the major contributors to the waste streams and PET is the most common semicrystalline thermoplastic polymer, which is used in the form of different products such as water bottles and films. PET bottles have been discarded after their single usage and they are contaminated a lot less than the other type of municipal solid wastes. Thus, their recyclability and reusability have been gaining attention in the last years by considering the environmental pollution. When the applicability of PET in various applications was considered, recycled PET by electrospinning could be a cost-effective and practical approach [17, 18]. Strain et al. fabricated large quantities of PET electrospun fibers to filter polycyclic aromatic compounds, persistent organic pollutant and nanoparticles. The thin PET fibers were evaluated for the filtration of tobacco smoke, which contains several thousands of particulates and vapor phase components [19].

Because the effect of these pollutants is a current concern, this way of recycling is a convenient approach for the environment. Zander et al. reported the water filtration efficiency of bottle-grade PET fibers over 99% filtration efficiency for 1 µm particles. Also, the elastic modulus of recycled fibers is better than the commercial products due to increased interactions from the additives, which were not present in the commercial ones [20]. For the wastewater treatment, adsorption is a widely used technique and electrospun membranes are other forms of adsorbent materials due to their high adsorption capacity, better reusability, ease of scale-up and no need for posttreatment. After a basic activation process, PET fiber substrates could be modified with chitosan, which is a convenient adsorbent to metal ions due to its amino and hydroxyl groups. Khorram et al. proposed an adsorptive membrane for the removal of Cr (VI) ions from the wastewaters with an economical and efficient method. PET bottle waste was electrospun into the form of fibers and activated by cold plasma followed by chitosan functionalization. The maximum adsorption capacity and reusability of membranes were evaluated under optimum conditions (Figure 10.5) [21].

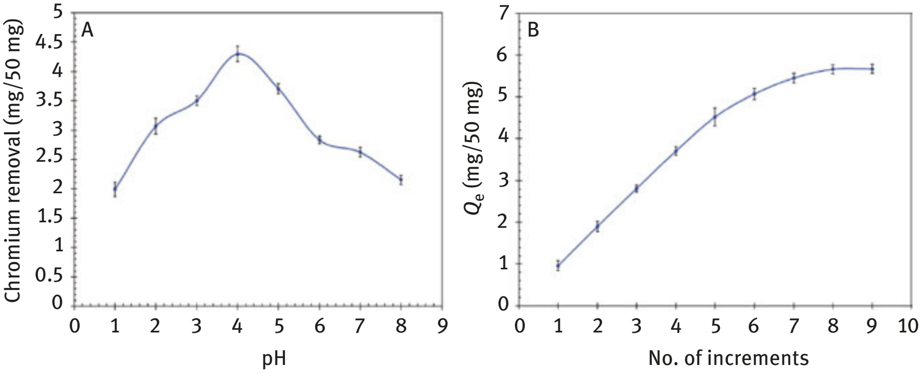


Figure 10.5: (A) The effect of pH on chromium removal and (B) cumulative amount of adsorbed chromium for filtration of 10 ppm chromium solution [Reprinted from Ref. [21]. Copyright (2017), with permission from Elsevier].

In another study, Zander et al. explored the usage of recycled PET electrospun fibers in water filtration for the removal of different size of particles ranging from 30 nm to 2.0 µm [22].

PS, especially EPS, is commonly used for insulation and packaging industries due to its versatility, dimensional stability, cleanliness and low cost. However, EPS wastes usually end up in landfill and occupy large spaces due to their low densities. Chemical and heating processed for EPS recycling is disadvantageous due to high-energy consumption. This obstacle can be overcome by using electrospinning due to its low energy requirement and fabrication of small size fibers. Shin et al. demonstrated the coalescence separation of water droplets in oil–water emulsions by using glass fiber media supplemented recycled EPS fibers. The effect of EPS fiber amount on the oil capture efficiency was evaluated, and 4% fiber amount is assumed optimal for pressure drop [23, 24].

One of the main products of chemical recycling for polycarbonate is bisphenol A [25], which is an endocrine disrupting compound. Although the conventional methods are convenient to recover waste PC materials, that is, compact disks, fabrication of fibrous materials by electrospinning of PC wastes is an appropriate method. Zander et al. carried out the formation of fibers from blends of two recycled polymers, which are PS and PC. The thermal and mechanical properties of these recycled blend fibers were investigated and the possible applications of these fibers were reported as ultra/microfiltration due to their improved elastic modulus (Figure 10.6) [20]. Isık et al. demonstrated the utilization of recycled high-impact PS (CD case) and EPS electrospun fibers for the removal of infectious clinical wastes due to their high protein adsorption capability. They also reported that the additives found in CD case,

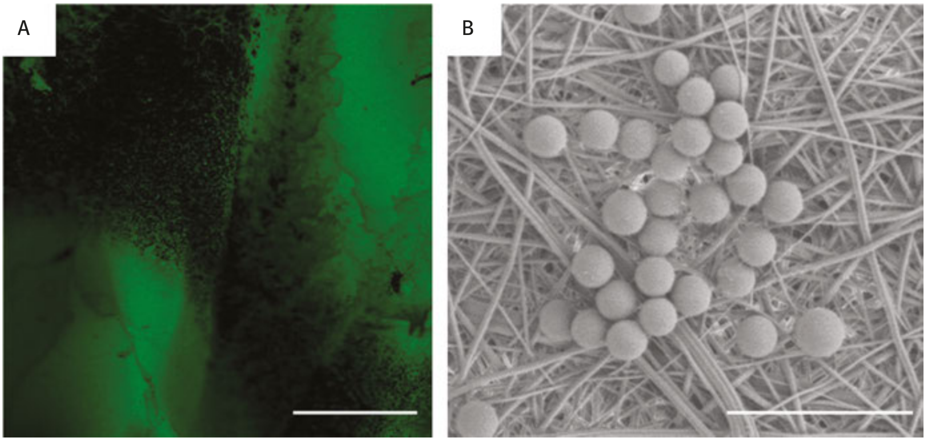


Figure 10.6: (A) Confocal laser scanning microscopy image of fluorescent ≈1 µm beads captured by the nanofiber mat and (B) SEM image of 1 µm beads on nanofiber mat. [Reprinted (adapted) with permission from Ref. [20]. Copyright (2015) American Chemical Society].

especially $CaCO_3$, enhanced protein adsorption capacity nearly eight times when CD case waste PS is compared with commercial PS [26]. Matulevicius et al. demonstrated the development of air filters from thermoplastic nylon and PS wastes by electrospinning. The filtration characteristics of electrospun filters have been evaluated by measuring the penetration of NaCl aerosol particles [27].

There is a considerable effort to create economic and environmentally sustainable polymeric membranes by using renewable sources rather than synthetic polymer membranes. Biopolymers are the recent and favorite resources as an alternative to synthetic polymers due to their biodegradability [28, 29] (Figure 10.7). By taking into consideration that keratin is one of the most abundant proteins, it could be evaluated in filtration membranes for the removal of hazardous substances. Moreover, keratin is an important renewable material and distinguished from the other proteins due to its high stability, which comes from its intramolecular structure. However, there is only one disadvantage that it has very low molecular weight that results in low physical properties, for instance, low mechanical properties. Thus, sometimes there is a need to blend this biopolymer with another suitable polymer for further applications. Aluigi et al. studied the air and water cleaning ability of keratin/polyamide 6 blend nanofibers by using chromium ions and airborne formaldehyde. The authors prepared different portions of blend solutions and fabricated filters. However, the keratin becomes soluble when its ratio in blend exceeds over half of the polyamide 6. Even at low keratin amounts, the membranes demonstrated a significant adsorption capacity to chromium ion and they are also good formaldehyde absorbers by reducing the airborne formaldehyde amount up to 70% [29]. The same group of authors also fabricated wool-derived keratin nanofibers by electrospinning for the selective removal of Cu(II) cations in the presence of Ni(II) and Co(II) ions. The results demonstrate that the adsorption of Cu(II) ions occurs by ion-exchange reactions, and the selectivity of nanofibers was reported as toward Cu(II) > Ni(II) > Co(II) [30].

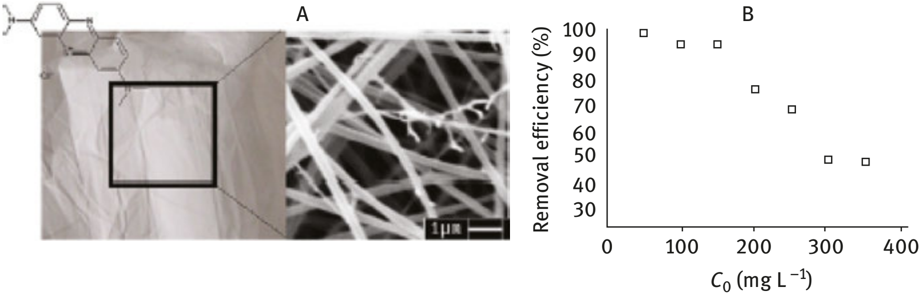


Figure 10.7: (A) Keratin nanofibrous membrane and related SEM micrograph, and (B) the effect of initial dye concentration on the removal efficiency of keratin membranes. [Reprinted from Ref. [28]. Copyright (2014), with permission from Elsevier].

Rice starch-based functional nanofibers have also interested by both scientific and industrial committees due to their biodegradability, biocompatibility and ease of formability. Woranuch et al. fabricated bio-based functional electrospun fibers by blending starch with poly(vinyl alcohol) for solution stability. They studied the solution parameters systematically to optimize the most plausible condition for good processability, well-defined morphology and uniform diameter. Also, the effect of β-cyclodextrin addition was investigated on the volatile organic compound adsorption capacity [31].

10.2.2 Photocatalytic applications

Fly ash is a by-product from coal combustion and it is a complex anthropogenic material that creates serious environmental and health concerns. Due to the increasing landfill cost, the recycling of fly ash gains an increasing attention, and the applications of waste fly ash take place in construction industry, ceramic industry, catalysis, environmental protection or valuable metal recovery [32]. By taking into consideration of this wide range of applications, fabrication of composite materials by electrospinning technique is a potential candidate as a recycling approach for fly ash. Also, fly ash has several favorable properties such as sphericity, porosity, nontoxicity, lightweight and high strength property, and being cost effective. Therefore, Saud et al. investigated the methylene blue adsorption/degradation of fly ash-doped TiO_2 nanofibers by electrospinning followed by calcination. Incorporation of fly ash into TiO_2 nanofibers strongly enhanced the photocatalysis and this reusable material can be used effectively for the purification of water [33] (Figure 10.8).

EPS wastes are also convenient candidates for the fabrication of composite materials for several applications. Rajak et al. investigated the photocatalytic activity of EPS by fabricating TiO_2/EPS composite fibers. The as-fabricated fibers showed a significant decrease in the concentration of a blue textile dye with 69% degradation [34]. In another study, Aluigi et al. prepared freestanding and flexible keratin nanofiber membranes by electrospinning. They mentioned that the problems are caused by industrial dye pollution and studied on a model system, which is prepared with methylene blue. The results show that proposed biodegradable keratin fibrous membranes are promising candidates for adsorption studies due to their large surface area and high porosity, and they are claimed to be regenerate followed by reusing due to their dynamic conditions [28].

10.2.3 Antimicrobial applications

Biomass pyrolysis and gasification result in the fabrication of an industrial by-product, tar, which is a potential carbon-based feedstock. However, the disposal of this product

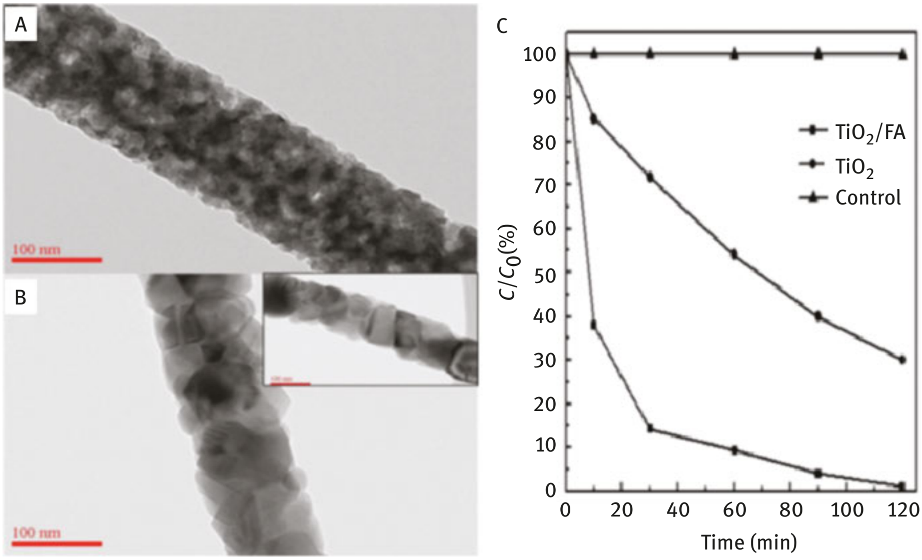


Figure 10.8: (A) and (B) TEM images of TiO_2 and fly ash/TiO_2 composite nanofibers and (C) comparison of methylene blue photodegradation by two specimens under UV radiation. [Reprinted from Ref. [33]. Copyright (2014), with permission from Elsevier].

is excessively difficult due to its complex chemistry and resistance to degradation. Due to its high carbon content, tar can be a low-cost precursor for the fabrication of carbon nanofibers (CNFs), which have promising applications in energy conversion, storage, gas adsorption and biomedical fields [35, 36]. Song et al. reported a novel route for the fabrication of porous CNFs with antimicrobial capability by electrospinning recycled tar and polyacrylonitrile (PAN) (Figure 10.9). As-prepared fibers demonstrated enhanced average fiber diameter distribution, surface roughness and antimicrobial capacity by the increment in tar content [37]. The same group of authors also investigated the effect of silver nanoparticle addition into the tar/PAN composite fibers on their antimicrobial activities. The resulting fibers have mesoporous characteristics with micropores, which come from the thermal decomposition of tar and phase separation of tar–PAN system [38]. Also, Saud et al. investigated the antimicrobial activity of fly ash doped TiO_2 nanofibers by electrospinning followed by calcination. Incorporation of fly ash into TiO_2 nanofibers strongly enhanced antibacterial resistance [33].

Regarding the sustainable material fabrication studies, natural or bio-based materials have been gaining attention in the recent years. These agricultural wastes or industrial by-products have several advantages such as their low cost and availability in large amounts. Woranuch et al. demonstrated silver nanoparticle added starch/PVA blend electrospun fibers and investigated the antimicrobial activity of these fibers. They reported that these fibers have superior bacterial inhibition against both

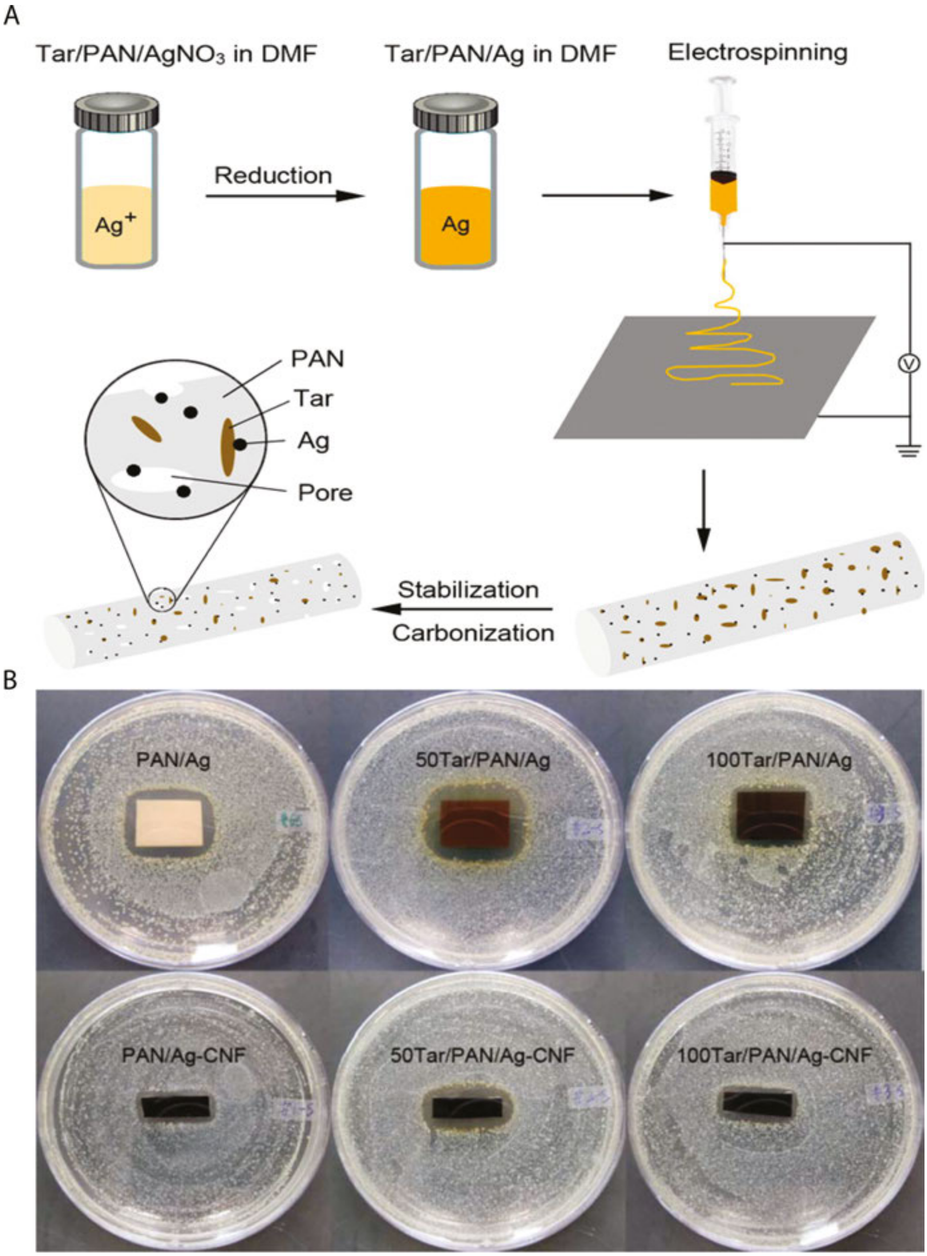


Figure 10.9: (A) Schematic illustrating the fabrication of the porous tar-derived CNFs through electrospinning followed by stabilization and carbonization processes and (B) antimicrobial activities of the as-spun nanofibers (upper row) and CNFs (lower row) with different tar contents against *S. aureus*. [Reprinted (adapted) with permission from Ref. [38]. Copyright (2015) American Chemical Society].

E. coli and *S. aureus* bacteria cultures [31]. Antibacterial activity of cellulose electrospun fibers was reported by Kampeerapappun et al. that they treated the cotton waste cellulose electrospun nanofibers with 3-(trimethoxysilyl) propyldimethyl octadecyl ammonium chloride and the results showed that proposed nanofibers exhibited excellent antibacterial activity against *E. coli* and *S. aureus* [39].

10.2.4 Battery and capacitor applications

Lithium-ion batteries (LIBs) are the commonly used power sources in recent years due to their stable cycling performances and they are suitable energy storage devices. However, there is a need to develop alternative anode materials for LIBs because the energy and power density are insufficient for large rechargeable devices [40]. Jiang et al. successfully synthesized silicon nanorods from industrial fly ash waste by electrospinning for the fabrication of LIB electrodes. Compared with the other literature results, this method has several advantages such as no need to delicate equipment and easy to scale up, high and sustainable silica derivation, and the integrity due to porous nanostructure of the material. When considering the cost-effectiveness and scalability of process, fly ash-derived silicon nanorods are effective materials for LIB anodes [41].

Apart from the aforementioned synthetic wastes, there are other less abundant wastes such as poly(vinyl butyral) (PVB). PVB is a commonly used adhesive in safety glass production due to its transmittance and superior adhesion. However, waste PVB materials are generally incinerated in landfill sites and cannot be recycled due to the costly pre-separation process. Park et al. synthesized CNFs from urea containing PAN/w-PVB (waste poly(vinyl butyral)) composite fibers (N-CNFO) via cost-effective electrospinning followed by carbonization processes. The unique open channels were created by the vaporization of w-PVB and provide numerous active sites on the surface of CNFs. The resulting material exhibits a high reversible capacity, superior rate capability and excellent cycling stability, and promising candidates for their utilization in the anodes of LIBs (Figure 10.10) [40].

The recent developments on the renewable polymers have been attracted attention on the LIB applications, too. The cellulosic fibers are another type of renewable raw materials due to their easy availability abundance, remarkable physical–mechanical properties and biodegradability. The utilization of cellulose acetate extract from cigarette filter tips and poly(vinylidene fluoride-*co*-hexafluoropropylene) (PVDF-HFP) blend solutions was processed by coaxial electrospinning, and Huang et al. fabricated a promising separator for high-performance LIBs. This study presents an environmentally friendly material, cellulose acetate, from waste cigarette filters and exhibits a separator with high storage capacity, better cycling feature, flame retardant property, excellent thermal

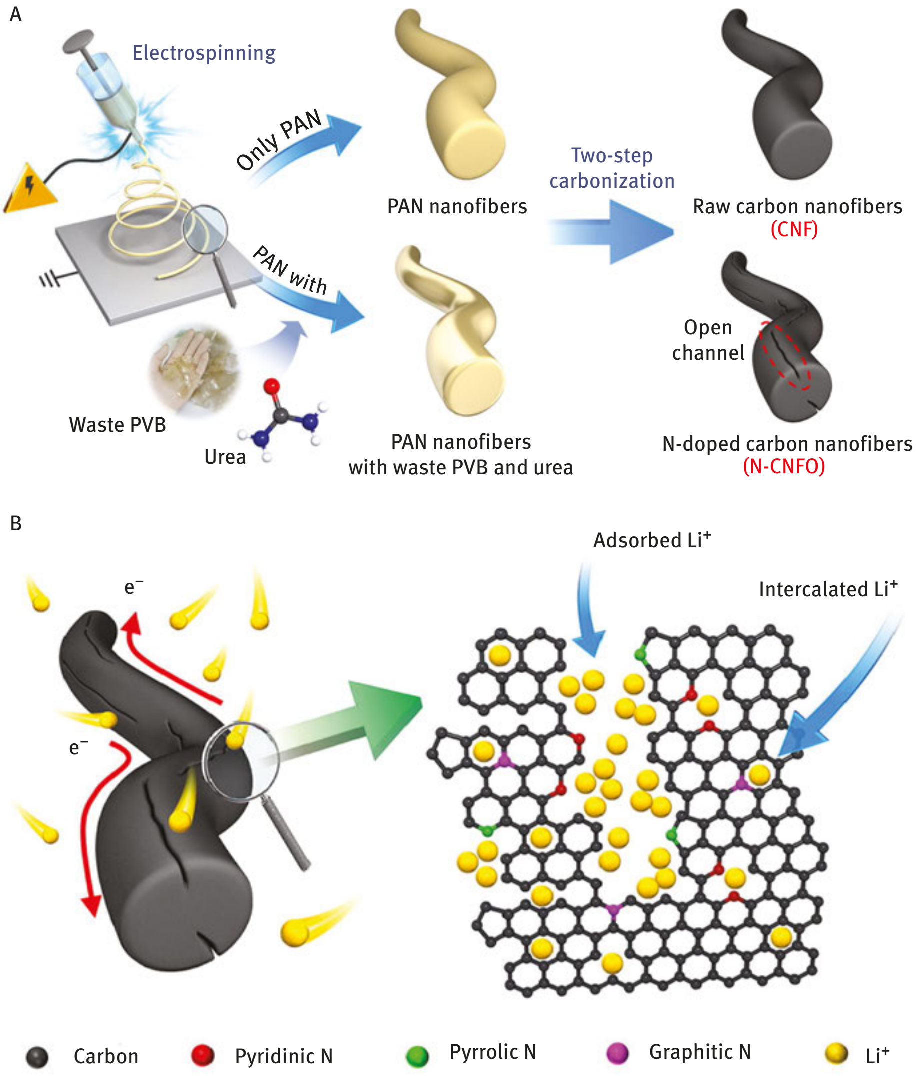


Figure 10.10: (A) Schematic illustration of the preparation of CNF and N-CNFO and (B) lithium-ion storage mechanism in N-CNFO. [Reprinted from Ref. [40]. Copyright (2017), with permission from Elsevier].

stability and enhanced rate performance [42]. Yang et al. developed a green method for the fabrication blend nanofibers from wheat straw and PAN precursors. These nanofibers are promising electrode materials with high specific capacitance and current density (Figure 10.11) [43].

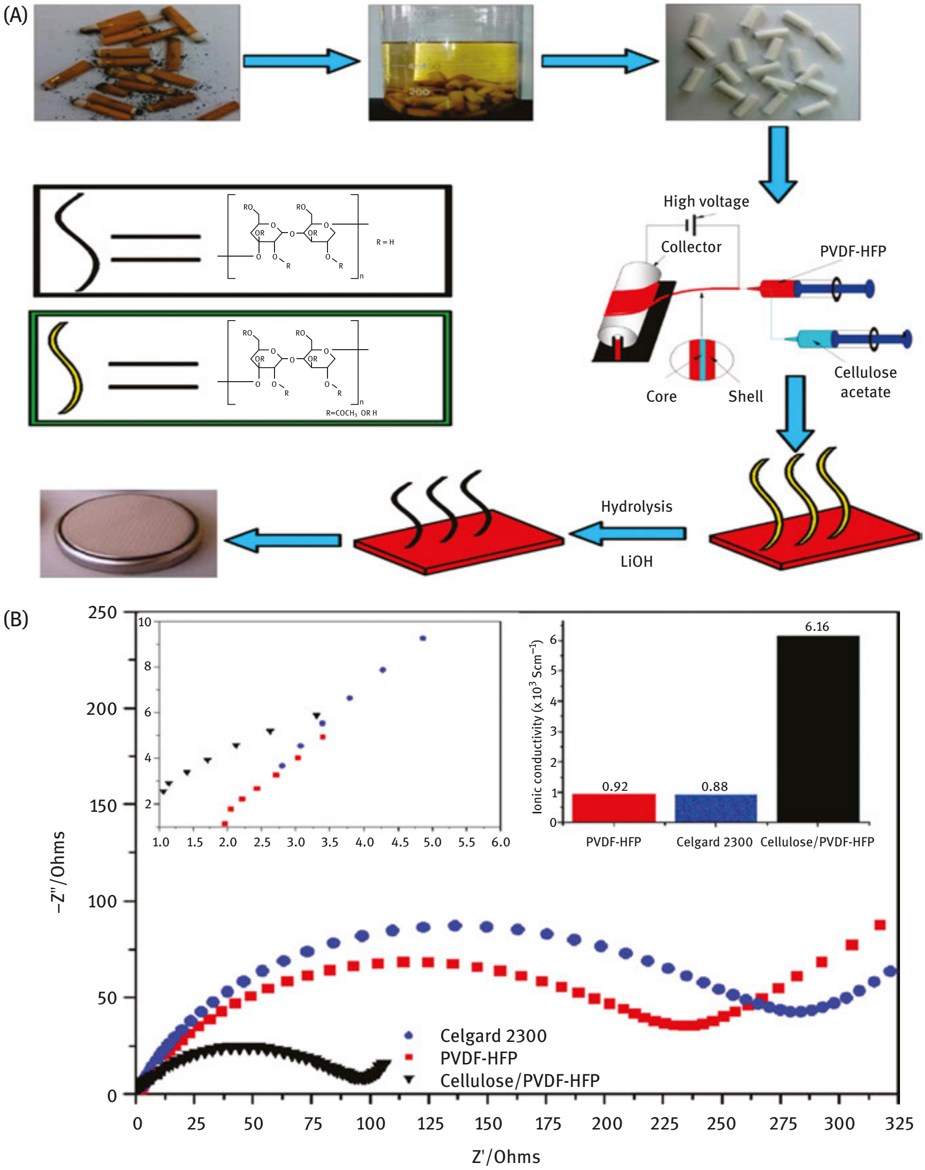


Figure 10.11: (A) Schematic illustration of the preparation process of cellulose-based coaxial nanofiber separators for lithium-ion battery and (B) Nyquist plots of Li/electrolyte-soaked separator/Li cells at 20 °C; insets are magnified Nyquist plot and ionic conductivity of separators. [Reprinted (adapted) with permission from Ref. [42]. Copyright (2015) American Chemical Society].

Lignin is also a green and economically viable precursor for the fabrication of electrode materials due to its obvious low cost and environmental benefits. It is the second most abundant polymer after cellulose. On the other hand, sodium- ion batteries have been gaining attention in recent years as promising electrical energy storage devices due to the abundance of sodium resources through the world. Jin et al. proposed PAN/lignin nanofibrous materials, which are mechanically flexible and have 3D interconnected structure. This composite electrode material exhibited a reversible capacity of about 292.6 mA h g^{-1} and high initial efficiency of 70.5% at a current density of 20 mA g^{-1}. Also, the proposed material has a good rate capability of 80 mA h g^{-1} at 1 A g^{-1} and high cycling stability over 200 cycles as 247 mA h g^{-1} at 0.1 A g^{-1}. These low-cost and freestanding nanofibers have outstanding electrochemical performances in SIBs and their green precursor source makes them a sustainable electrode material [44].

10.2.5 Biomedical applications

Biomimetic approaches have been used in tissue engineering, which combines the principles and methods of life sciences. The control of cellular responses, manipulation of healing environment to control the structure of regenerated tissue, production of cells and tissues for transportation into body, and development a quantitative understanding of biological processes are important issues in biomedical field [45]. Wound healing is one of these biological applications that is a complex process and requires collaboration of many cell strains and their products [46]. The nonwoven tissues could be used for wound healing applications to protect the tissue damage against any infections. Morganti et al. developed lignin-doped chitin nonwoven tissues to represent a skin-friendly and 100% biodegradable tool for wound repair. During wound healing, matrix reorganization process is assured by matrix metalloproteinase (MMPs), which has an important role in pathological tissue repair, fibrotic repair and scarring remedies [47]. The proposed material could modulate MMPs and reduce the dependence from the fossil fuel resources by encouraging the application of these biomaterials as a biomedical tool [48]. Sericin has excessive properties that it is biocompatible, biodegradable, antibacterial, UV and moisture absorbent, antioxidant and wound healing material [49]. In tissue engineering, the desirable properties of extracellular matrix are met by sericin. Eslah et al. fabricated PVA–sericin nanofibrous materials by electrospinning for the utilization of sericin in potential tissue engineering applications [50].

Plant extracts have extraordinary influences on various diseases and nearly 25% of drugs are derived from medical plants. *Indigofera aspalathoides* (*I. aspalathoides*), *Azadirachta indica* (*A. indica*), *Memecylon edule* (*M. edule*) and *Myristica andamanica* (*M. andamanica*) have been used for wound healing since the ancient times, and their application in this process was demonstrated several times in literature. However, there is a disadvantage that plant extracts are in oily or hydrogel forms and it is hard to shape them during their utilization. Jin et al. developed a suitable approach for the fabrication of plant extract containing wound-healing materials by electrospinning. The individual plant extracts were blended with polycaprolactone, and the cell biocompatibilities of these composite fibers are evaluated. The results of F-actin and collagen staining confirmed that PCL/*M. edule* composite fibers are the most suitable substrates for tissue engineering applications [51]. The antioxidant property of phenolic compounds has been used by Vashisth et al. The authors used agrowaste-derived ferulic acid, which is a food additive to prevent peroxidation of lipid, but limited availability. Ferulic acid was encapsulated by poly(D, L-lactide-*co*-glycolide)/polyethylene oxide (PEO) polymer blend and nanofibrous membranes were fabricated via electrospinning. The resulting composite fibers showed cytotoxic and antioxidant activities against HepG2 cells [52]. Peršin et al. also used plant extracts for the development of antioxidant and antimicrobial materials. The olive leaf extract was blended with carboxymethyl cellulose, alginate and PEO for the fabrication of electrospun fibers, which were then examined in wound healing application. The oil leaf extract increased the solution conductivity and decreased the surface tension by making easier the electrospinning process. Also the phenolic components in electrospun fibers are responsible for the antioxidant property and the proposed fibers show antibacterial property beside the Korsmeyer–Peppas model release mechanism [53]. Guzman-Puyol et al. also showed the utilization of fibroin and cellulose (from waste parsley) blends for the fabrication of biocompatible nanofibers, which can have adhesion and proliferation properties of fibroblasts. Also the addition of cellulose from parsley enhances the stiffness and elastic modulus of fibrous material. The proposed parsley/fibroin mats show excellent biocompatibility and could extend the utilization of these naturally derived polymers in sustainable management of food waste (Figure 10.12) [54].

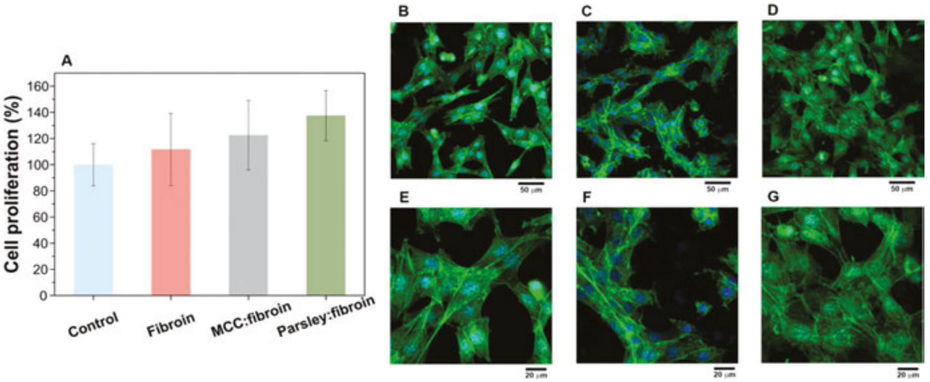


Figure 10.12: (A) Viability of fibroblast cells (MTT ('3-(4,5-Dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromidefor') assay) on the different types of nanofibers, and (B)–(G) fluorescence micrographs of fibroblast cells cultured on parsley/fibroin nanofibers. [Reprinted (adapted) with permission from Ref. [54]. Copyright (2016) American Chemical Society].

Ramphul et al. reported the fabrication of composite nanofibrous membranes from cellulose blended poly(L-lactide) or polydioxanone. The cellulose was extracted from bagasse, which is the waste of sugarcane with approximately 30% cellulose content. For the enhanced processability of solutions by electrospinning, cellulose was converted to cellulose acetate and blended with biocompatible polymers. The as-prepared fibers show biocompatibility proved by in vitro fibroblast cell studies, and MTT assay indicates their higher cell densities than the control samples [55]. Another recycling approach for sugarcane wastes was reported by Correia et al. such that polyhydroxybutyrate was extracted from sugarcane wastes and processed by electrospinning. The proposed electrospun fibers demonstrated suitable materials for biomedical applications due to their cell adhesion ability [56].

Polyhydroxyalkanoates are biopolyesters produced by bacteria as carbon storage materials. However, their high operational cost is the main problem for their use in packaging materials, although they could be replaced with PET in industry. Thus, Martínez-Sanz et al. reported the synthesis of polyhydroxybutyrate-*co*-hydroxyvalerate using food industry waste feedstocks, which are cheese whey and olive oil wastewaters, as substrates for the fabrication of bacterial cellulose reinforced nanocomposites by melt compounding. The proposed materials are suitable for food packaging applications [57]. In another study, PHA production was achieved by valorization of crude glycerol waste from biodiesel plant. The electrospun PHA membranes were tested in terms of cytotoxicity, hMSC adherence and proliferation in vitro, and it is claimed that they are potential candidates in regenerative medicine and tissue engineering applications (Figure 10.13) [58].

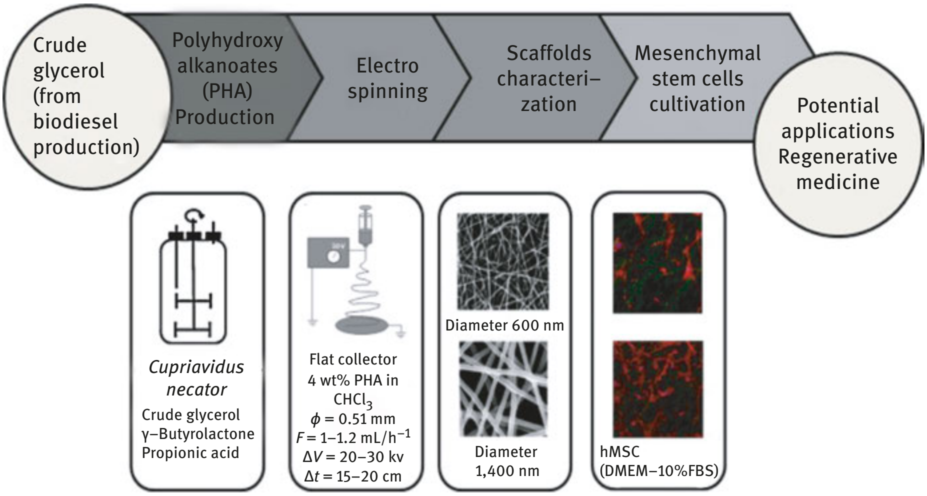


Figure 10.13: Schematic of integrated approach for waste glycerol bio-valorization into fabrication of electrospun scaffolds for stem cells. [Reprinted from Ref. [58], Copyright (2014), with permission from Elsevier].

There is a wide range of agricultural wastes that could be recycled and processed for their utilization in biomedical field. Corncob and wheat straw waste materials have also found an application in delivery systems for bioactive and functional ingredients. Kuan et al. treated the above-mentioned agricultural wastes and processed by electrospinning. The results showed that the materials are potential candidates for bioactive and nano-sized delivery agents due to their mineral binding capability (calcium, copper, iron and zinc), DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging ability and water holding capability [52]. Living functional cell containing composite fibers were also reported by Letnik et al. that the living cell, yeast, was isolated from olive mill wastewaters. The immobilized yeast was encapsulated by coaxial electrospinning, PVDF-HFP shell and yeast/PVP core. The resulting coaxial fibers have a unique structure and could be used in phenol degradation and ethanol fermentation applications (Figure 10.14) [59].

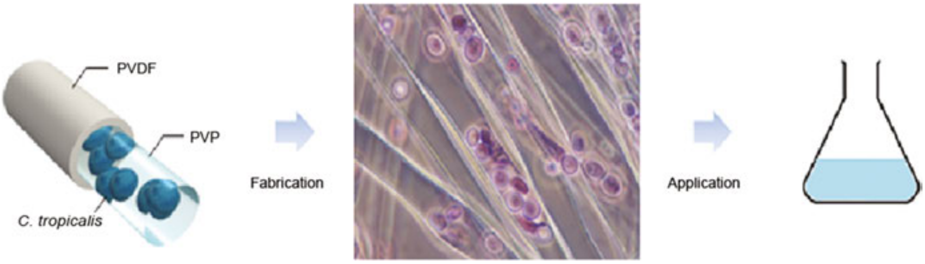


Figure 10.14: Schematic representation of PVDF-HFP@PVP/yeast composite fibers. [Reprinted (adapted) with permission from Ref. [59]. Copyright (2015) American Chemical Society].

10.2.6 Other applications

Dyeability of PET fibers fabricated from waste bottles was reported by Mahar et al. for advanced apparel applications. Their low energy consumption, less processing time, low material cost, good color yield and high mechanical strength make these recycled fibers favorable than the previously reported ones [60]. The encapsulation of magnetic or conductive materials was also studied by using recycled PS cups (EPS waste) for the determination of thermal, electrical, magnetic and surface properties of composite fibers. Khan et al. converted recycled EPS into fibrous form by electrospinning with the addition of multiwall carbon nanotubes and NiZn ferrite nanoparticles. The results showed that ferrite-based recycled EPS fibers show superparamagnetic behavior in addition to the enhancement of superhydrophobic, thermal conduction and dielectric constant properties. These composite fibers are asserted to be promising materials for diverse industrial applications [61].

Because of the low surface energy and roughness of materials fabricated from PET, they possess highly hydrophobic character, which represents a less fouling resistance than the hydrophilic ones. Thus, the improvement of PET fibrous membranes' hydrophilicity is an important issue in biological systems [62]. Lignocellulosic sisal fiber reinforced PET fibers were reported by Santos et al. that the contact angle of fibers was claimed to vary from 134° (hydrophobic) to 0° (superhydrophilic) (Figure 10.15), thereby both stiffness and hydrophilicity of electrospun fibers could be controlled with these composite fibers [63].

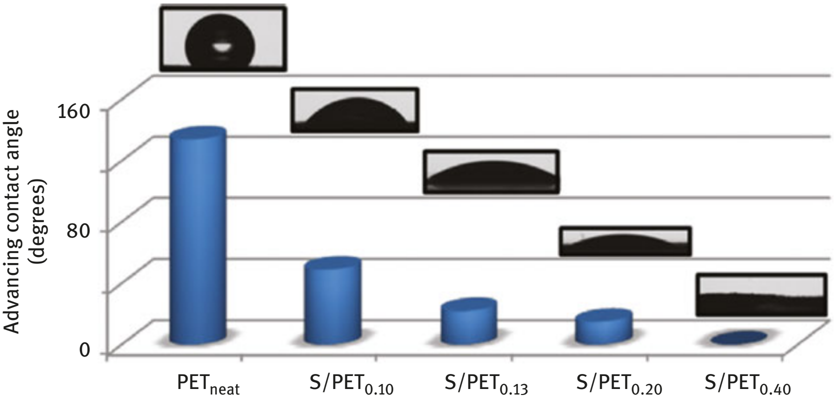


Figure 10.15: Advancing contact angle for PET_{neat} and S/PET electrospun mats and respective snapshots taken after the first/second of contact between a water droplet and its surfaces. [Reprinted from Ref. [63]. Copyright (2015), with permission from Elsevier].

10.3 Conclusion and future perspective

Electrospinning has been started to use for recycling purpose due to being cost effective and becoming diversified easily. This recent recycling approach minimizes the utilization of primary raw sources and provides the manufacturing of the secondary materials by using the plastic waste, which create considerable environmental problems. These resulting secondary materials take place in several applications such as biomedical field, photocatalysis and battery production. However, there is an adverse affect of this method from the environmental point of view that solvent-based approach in electrospinning could be harmful. Due to the evaporation of organic solvents during the electrospinning process, aerosol formation possibility goes up dramatically and the atmosphere as well as people could be affected in a harmful way. To overcome this adverse affect of this approach, melt electrospinning method could be applied for the recycling of plastic wastes without any requirement of organic solvents. The plastic waste materials could be utilized by melting with an extruder and the resulting melt could be electrospun under high potential difference in a combined extruder–electrospinning system. Thus, dangerous wastes could be remediated by recycling of plastic waste without any adverse affect.

Abbreviations

AFD	Average fiber diameter
A. indica	*Azadirachta indica*
CMC	Carboxymethyl cellulose
CNFs	Carbon nanofibers
DPPH radical	2,2-Diphenyl-1-picrylhydrazyl
E. coli	*Escherichia coli*
EPS	Expanded polystyrene
FESEM	Field emission scanning electron microscopy
I. aspalathoides	*Indigofera aspalathoides*
HDPE	High-density polyethylene
LIBs	Lithium-ion batteries
LDPE	Low-density polyethylene
MMP	Matrix metalloproteinase
MTT	3-(4,5-Dimethylthiazol-2-yl)-2,5-Diphenyltetrazolium bromide
M. edule	*Memecylon edule*
M. andamanica	*Myristica andamanica*
POPs	Persistent organic pollutant
PAN	Polyacrylonitrile
PCL	Polycaprolactone
PC	Polycarbonate
PAHs	Polycyclic aromatic compounds
PDX	Polydioxanone
PE	Polyethylene
PEO	Polyethylene oxide
PET	Polyethylene terephthalate
PHAs	Polyhydroxyalkanoates
PHB	Polyhydroxybutyrate
PHBV	Polyhydroxybutyrate-*co*-hydroxyvalerate
PLA	Poly(lactic acid)
PLLA	Poly(L-lactide)
PP	Polypropylene
PS	Polystyrene
PVA	Poly(vinyl alcohol)
PVB	Poly (vinyl butyral)
PVC	Polyvinyl chloride
PVDF-HFP	Poly (vinylidene fluoride-*co*-hexafluoropropylene)
PVP	Polyvinyl pyrrolidone

SEM	Scanning electron microscope
SIBs	Sodium-ion batteries
S. aureus	*Staphylococcus aureus*
TEM	Transmission electron microscopy
UV	Ultraviolet
VOC	Volatile organic compound
w-PVB	Waste poly(vinyl butyral)

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