A review of multifarious applications of Poly (lactic acid)

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Abstract:

Polylactic acid (PLA) is considered to be a promising alternative to petroleum-based polymers due to its renewability, biodegradability, biocompatibility and good mechanical properties. Because of the high cost, the applications of PLA were limited to the medical field. Over the past decade, improvements in polymerization allow the economical mass production of high molecular weight PLA. Therefore, the applications of PLA have recently spread to domestic, commercial packaging and textile applications. This review outlines the chemical, thermal characteristics of PLA and discusses the use of PLA in medical applications such as sutures, stents, drug carrier, orthopaedic devices, scaffolds, as well as commercial applications in textile and packaging fields with superior properties such as high wicking performance, good dyeability, antibacterial feature, good UV resistance, high water vapour transmission rates, shrink wrapping and dead fold property. While the drawbacks of PLA utilized in these fields are also discussed. It is clear that the advantages of using PLA outlined in this review will ensure that the market for PLA products will continue to expand.

1. Introduction

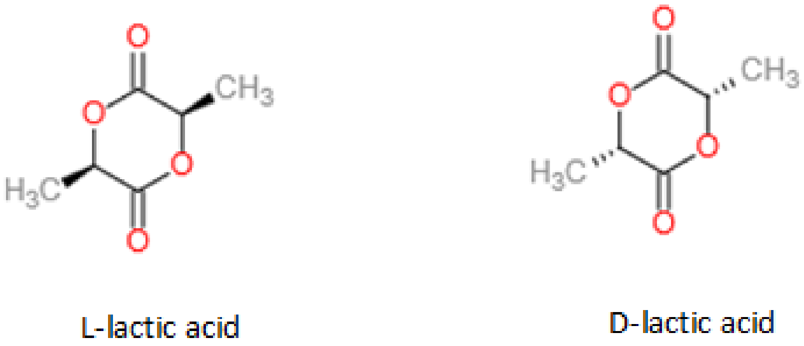
Polylactide acid (PLA) is derived from renewable and degradable resources such as corn and rice and decomposes via simple hydrolysis into water and carbon dioxide [1]. PLA has received much attention in the last decade not only because of the potential to replace petrochemical plastics, which are associated with environmental pollution and solid waste disposal problems, but also because of its relatively high strength, excellent biodegradability and good biocompatibility [2].

PLA is not a new material, indeed the synthesis of PLA was started as early as 1800s, but it has taken long time to reach production viability. In the early stage, PLA was limited to use in biomedical devices until last decade due to the high production cost, low availability and limited molecular weight [3]. Since 1990s developments in the manufacture technology, high molecular weight PLA has been produced in large volume and become affordable in packaging, textile applications, and could reasonably substitute conventional polymer [4]. Global PLA production capacity has grown dramatically and is expected to be 800,000 ton/year by 2020 [5]. Meanwhile, the global demand for PLA is also rising rapidly, Corbion Purac as a leading lactic acid supplier has announced that it will enter the PLA production business [6], and NatureWorks has recently started exploring a new feedstock: methane to meet this huge demand for PLA [7].

There are a lot of publications regarding synthesis of PLA and its medical applications, but not many in commercial applications. Hence, this review is dedicated to present the recent development in both medical and commercial applications.

2. Characteristics of PLA

PLA is a long linear chain, made up with repeated monomer unit: lactic acid (LA). LA exists in two enantiomeric forms: L- and D-optical isomer (Figure 1). The majority of fermentation processes produce predominantly the L-isomer. Therefore, the lactic acid is predominantly L-type. But the L-lactic acid can racemise under certain reaction conditions and convert to another isomer, the D-lactic acid. The presence of equal amount of L- and D-type of lactic acid leads to meso-lactic acid [8]. PLA that purely composed of L-lactic acid or D-lactic acid is called PLLA or PDLLA respectively, while PLA that composed of meso-lactic acid is called PDLLA or meso-PLA. The commercial PLA is a copolymer of PLLA and PDLLA [9].



L-lactic acid

D-lactic acid

Figure 1: The chemical structure of two types of lactic acid.

The arrangement of L- and D-lactic acid or the stereochemical structure determines almost all the properties of PLA. The ability to control the stereochemical architecture allows precise control over the speed and degree of crystallinity, the mechanical properties, and the processing temperature of the material [10]. Nuclear magnetic resonance (NMR) is a useful method to investigate the stereochemical structures. The characteristic peaks of PLA are slightly different depending on how PLA is polymerized. PLA produced by direct condensation polymerization has 5 characteristic peaks at 169.27, 169.31, 169.42, 169.49 and 169.66ppm. The signal at 169.66ppm can be assigned to carbonyl carbon atoms of successive L-lactic acid units, while the other four signals can be assigned to carbonyl carbons influenced by D-lactic acid units. Whereas PLA produced by ring opening polymerized has another peak at 173.75ppm for L/D-PLA, since L- and D-lactic acid are introduced in pairs in ring opening polymerization [10], [11]. PLLA and PDLA that are composed of highly organized L-lactic acid and D-lactic acid respectively, result in high crystalline polymer with a melting temperature of 175 - 180°C and a glass transition temperature of 60 - 70°C [12]. The introduction of meso-lactic acid or D-lactic acid results in reduction in melting temperature and crystallization behaviour of PLA, PLA can be completely amorphous at D-lactic acid content higher than 12-15% [13]. Compared to other thermoplastics, PLA has relatively high glass transition temperature and low melting temperature [3]. A DSC thermogram curve of a commercial semicrystalline PLA is presented in figure 2. PLA exhibits a Tg at 62.86°C, the re-crystallization exothermic peak between 80 and 140°C and a melting endothermic peak at 169.12°C. PLA is a slow crystallizing material [10]. Shi and co-workers investigated isothermal crystallization behaviour of PLA and reported a crystallization half time of 37.7 min in their work [14]. High cooling rate from the melt doesn't give enough time for PLA to recrystallize and usually results in amorphous PLA, which typically happens in injection moulding process [15], [14]. Annealing after injection moulding was reported to increase the degree of crystallinity of PLA and improve mechanical and heat resistance performance [16], [17]. Various nucleating agents, such as Talc and phthalimide, have been reported to be efficient to improve crystallization behaviour of PLA [18], [19].

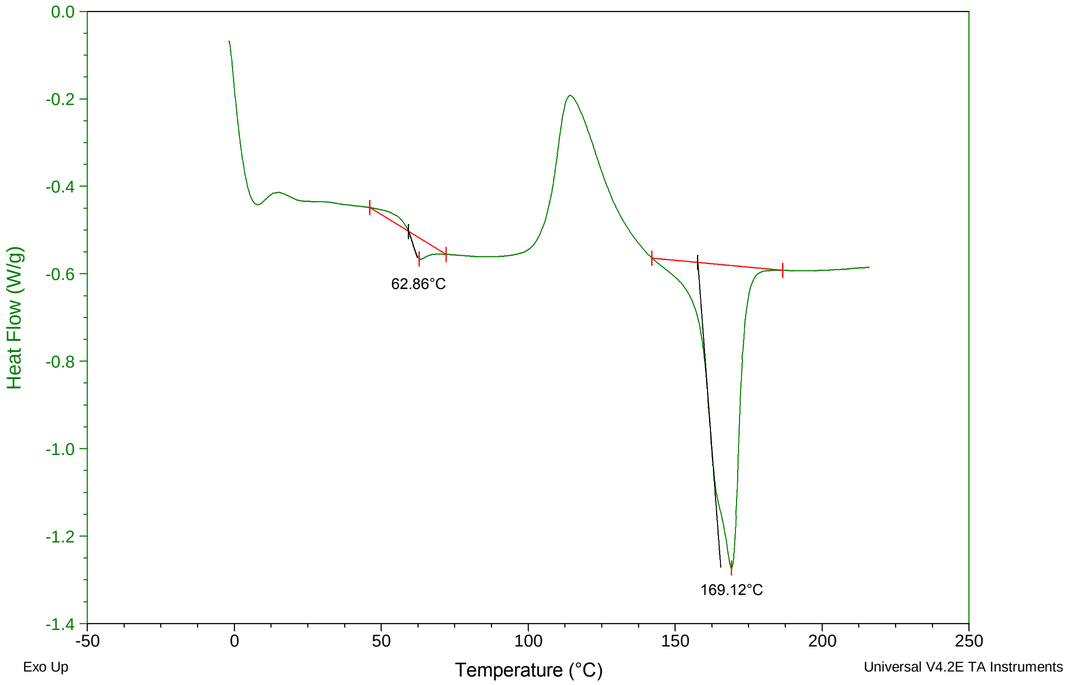


Figure 2: DSC thermogram of PLA from NatureWorks Ingeo 7032D.

PLA belongs to aliphatic esters family. It is very easy to recognize a strong C=O stretching absorption band in the region of 1870-1540 cm^{-1} in Fourier transfer infrared spectroscopy (FTIR) spectrum, since this band has a relatively constant position, high intensity and relatively freedom from interfering bands [20]. The other characteristic absorption bands are –OH stretch located at 3571 cm^{-1}, C-H stretch at 2996.53 and 2987.75 cm^{-1} (Figure 3) [21].

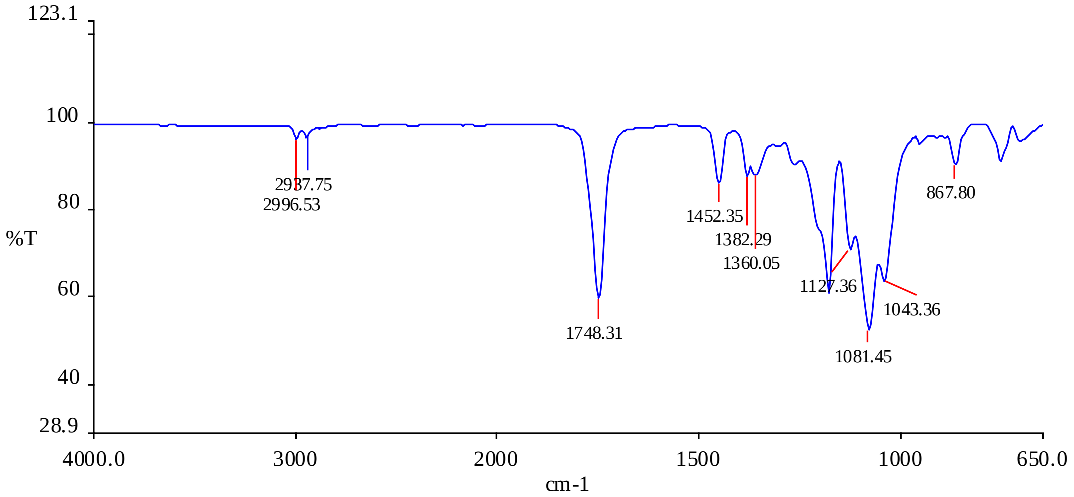


Figure 3: FTIR spectrum of PLA from NatureWorks Ingeo 7032D.

Semicrystalline PLA is a relatively strong biodegradable polymer with tensile modulus of 3000-4000MPa, tensile strength of 50-70MPa and elongation at break of 2-10% [12]. However, brittleness and poor thermally stability are the major drawbacks of PLA and limit its applications. Several modification methods have been investigated to reduce the brittleness of PLA, including using plasticizers such as oligomeric lactic acid [9], [22], glycerol [9], fatty acid esters [23], citrate family[24], [25]; blending PLA with various polymers such as Polycaprolactone (PCL) [26], [27], polyethylene oxide [28], polyethylene glycol [29], [30]. Bhardwai & Mohanty reported to improve the toughness of PLA dramaticaly by forming a hydroxyl functinal hyperbranched polymer in-situ cross-linked with polyanhydride in PLA matrix during melt process [31]. Generaly, the brittleness of PLA has been reported to be improved, however, leaching during use and biocompatibility issues remain to be problematic [32].

In terms of poor thermal stability, PLA is reported to undergo thermal degradation at 200°C [3], [10], [2]. Thermogravimetric analysis (TGA) and gel permeation chromatography (GPC) are essential methods to observe the thermal degradation behaviour of PLA. The incorporation of various fillers into the PLA is a useful approach for enhancing its thermal stability, mechanical property and hydrolysis resistance [1]. Many fillers have been utilized in combination with PLA, including silica nanoparticles [33], [34], carbon nanotubes[35], bamboo fibres [36], hydroxyapatite fibres [37], montmorillonite [38], halloysite nanotubes [39].

3. PLA in Biomedical Applications

Biodegradability is a key advantage of PLA medical devices. PLA medical devices can degrade slowly after they have fulfilled their function, hence they can avoid secondary surgery to remove the implants [40], and eliminate long-term complications such as persistent body immune rejection and potential bacterial infection [41]. The degradation process of PLA is simple hydrolysis of the ester bond and does not require the presence of enzymes to catalyse this hydrolysis [10].

Biocompatibility is another important feature of PLA medical devices. Comprehensive studies in biocompatibility of PLA have been carried out, and the majority of results indicate that PLA is sufficiently biocompatible, with a minority suggesting otherwise [42]. PLA has a long safety history in medical applications. It has been approved by the US Food and Drug Administration (FDA) and other regulatory agencies in many countries for implantation in the human body [41]. Based on this safety approval, a variety of medical implants made from PLA have been developed, such as sutures, stents, and bone fixation devices, such as screws, pins, rods and plates a variety of which are detailed in this review.

3.1 PLA based sutures

Generally, sutures are made up of polymeric fibres, either natural or synthetic. Natural fibres are collagen, cotton, silk, or linen, while synthetic fibres can be poly (propylene) (PP), poly (ethylene glycol terephthalate) (PET), poly (butylene glycol terephthalate) (PBT), nylons, polyamide (PA), and some biodegradable synthetic fibres such as PLA based polymers. Natural fibres cause a more intense inflammatory reaction than synthetic materials [43]. Therefore, synthetic sutures are commonly used in wound closure, and among them biodegradable sutures, which are defined by the loss of their strength within 60 days after placement [41], are mainly used for healing internal wounds to avoid secondary removal [44].

The polymers used for biodegradable sutures include Poly (glycolic acid) (PGA), PLA, polyglyconate (PG), poly (L-lactide-co-ε-caprolactone) (PLA-ε-CL) (Pillai & Sharma 2010). The common commercial biodegradable sutures and polymers are listed in table 2. PLA has a long degradation period compared to other biodegradable polymers, hence PLA alone is not suitable for short period applications, but copolymerization of lactic acid with other monomers can modify the degradation rate and become suitable for these applications. A typical PLA copolymer for sutures applications is poly (lactic-co-glycolic-acid) (PLGA).

PLA sutures have several advantages compared to other suture materials. The initial strength of the PLA fibres is lower than that of many commercially available sutures such as Vicryl®, Maxon®and Ethilon (Nylon 6 and Nylon 66, manufactured by Ethicon), but PLA sutures are superior to that of Ethilon and comparable with that of Vicryl® in terms of handling characteristics [45]. PLA sutures also have more prolonged tensile strength retention (TSR) than that of Maxon® and they have been suggested as an alternative in the repair of the Achilles tendon [46]. SR-PLA sutures exhibited the most prolonged strength retention and could be applied to the closure of wounds that need prolonged support, such as bone repair [47]. Recently, a drawn PLLA suture with helical structure was investigated in rat patellar ligament and reported to generate a piezoelectric charge under cyclically applied tensile stress; a significantly higher ossification was observed around the implanted helical PLLA suture in the rat keen joint compared to untwisted PLLA suture, which suggested helical PLLA fibre may be useful for surgical suture or artificial ligament connecting to the bone [48].

Antibacterial sutures are a recent development in the wound closure area. Surgical site infections (SSI) are the challenging complications, anti-microbial coated sutures can effectively defend against various bacterial pathogens [49]. Vircryl Plus is made from 90% glycolide and 10% L- lactide, and produced by Ethicon. This suture contains Irgacare MP (troclosan), a broad-spectrum antibacterial agent [50]. Since the first triclosan-resistances were reported recently, an alternative chlorhexidine was coated on sutures by Obermeier et al. and they demonstrated the high antimicrobial efficacy against *S.aureus* in vitro [49].

PLA based fibres can also be fabricated into mat with various shapes used in medical treatment. Behrens et al. reported the use of solution blow spinning to generate PLGA nanofibers on the wound surface in situ, utilizing a commercial airbrush and compressed CO_2 [51]. The PLGA fibres airbrushed onto the incision of the wound can take the shape of the area and promote healing [52]. Zhang et al. developed multilayered PLA electrospun nanofibres with cisplatin loaded. They reported that by covering the surgical site with this PLA mat following resection of subcutaneous liver cancer in mice, retarded tumor recurrence, prolonged survival time of mice and less systemic toxicity were observed compared with other treatment groups [53].

Similiarly, Zhang et al. implanted PLA nanofiborous mats loaded with 5-fluorouracil and oxaliplatin into mice with colorectal cancer, and they found suppressed tumor growth rate and prolonged survival time of mice in comparison to drug-free control group [54].

Table 2: Common commercial biodegradable sutures [45], [55]

Suture name	Material	Manufacture
Dexon®	Polyglycolide (PGA)	Davis & Geck Corp
Vicryl®	poly(lactic-co-glycolic-acid) (PLGA)	Ethicon
Maxon®	Polyglyconate	Davis & Geck Corp
Monocryl®	Polyglycolide co-ε-caprolactone	Ethicon
Biosyn®	Polydioxinone co-trimethylene carbonate-co-glycolide	US Surgicals
Bio-Anchor	PLLA	Mitek
Vicryl Rapide™ (Polyglactin 910)	Glycolide/PLLA	Ethicon
Bio-PushLock	PLLA	Arthrex
Polysorb	PLLA/PGA	Covidien
Vicryl Plus	Glycolide/PLLA with Triclosan	Ethicon

3.2 PLA based orthopaedic fixation devices

Tremendous advances have been made in orthopaedic field over the past two decades. Biodegradable polymers have wide applications in this field, from bone regeneration scaffolds to all sorts of fixation devices. Bone regeneration scaffolds will be discussed in tissue engineering section, hence orthopaedic fixation devices are emphasised in this section. PLA as a biodegradable polymer has a very long history of use in orthopaedic field and some results indicate that it is superior to non-biodegradable metallic materials in some applications.

When a weight bearing system is made up with two or more materials, as such a plate and screws used to stabilise a fracture, the load, stress and strain will be placed on the stiffer component and thus the bone will not be exposed to physiological loading necessary for the normal remodelling process to occur. This is called stress shielding and remains a concern in orthopaedic field [56], [57]. The internal fixation of fractured bone by means of metallic devices results in reduced stress stimulation on the bone, which leads to osteoporosis, fracture or loosening of implant in the later stage of healing [58]. Intensive research in novel materials to reduce stress shielding for bone fixation has been carried out, e.g., carbon fibre/Flax/Epoxy composite bone fracture plate [59]. Biodegradable inserts such as PLA plates would remain stiff and rigid enough to support the load until the bone has healed sufficiently to do so without assistance avoiding stress shielding [60], [61], [62] and enabling increased micromotion in the axial plane to promote healing during the union phase [63]. Chen et al. investigated the use of PLA plate (95%L- lactide/5%D-lactide) in rabbit model and reported that the load-carrying duty was shifted to PLA plate in the early stage of healing of the fractured bone. However, with the progression of bone healing, the stiffness of the fractured bone increased and regained its original load-bearing function as the PLA plate degraded [64]. It is interesting to note that the recent development in bone fixation devices has evolved to internal fixation devices since they are biologically superior to the traditional external fixation devices. The intramedullary bone stents made from composite containing PLA matrix is under developing [57]. Furthermore, crystalline PLLA is a piezoelectric material with a high shear piezoelectric constant [65], which means it can generate electrical charge in response to pressure or stress, similar to the response of healthy bone. Abundant clinical studies and animal experiments have reported the improved bone healing progress due to the electrical stimulation [66], [67], [68]. Hence, piezoelectric materials such as crystalline PLLA caught a lot of attentions in orthopaedic applications [69], [48].

Semicrystalline PLA is one of the strongest among biodegradable polymers. The superior mechanical strength of PLA makes it a promising material in orthopaedic fixation field. The Common commercially available biodegradable bone fixation nails and screws were listed in table 3. Nuzzo et al. conducted a study to characterize mechanical properties of the fixation devices and reported that SmartScrew possessed the best compression force and pullout strength when compared with Smart Nail, LactoNail and ReUnite Screw [70]. Self-reinforced polylactic acid (SR-PLA) with further improved mechanical properties was investigated by Sun et al., where SR-PLA screws were implanted into 37 patients for 18 months for the treatment of cancellous bone fracture. The study concluded that the SR-PLA screw was a rational option in fracture internal fixation of cancellous bone since no infection, aseptic inflammation or osteolysis was reported and the general percentage of fitness was up to 86.48% [71].

Table 3: Common commercial available biodegradable bone fixation nails and screws [70], [55].

Product name	Materials	Manufacture
SmartNail	PLLA	Conmed Linvatec
LactoNail	PGA/PLLA	Arthrotek Biomet
SmartScrew	PLLA	Conmed Linvatec
ReUnite Screw	PGA/PLLA	Arthrotek Biomet
BioComposite	Biphasic Calcium/PDLLA	Arthrex
Hexalon^{TM}	L–lactide/D-lactide/ Trimethylene carbonate	Inion Ltd.
BioCore	PLLA/PGA	Biomet
The Wedge	SR PDLLA	ConMed Linvatec

Another feature of PLA orthopaedic devices is the possibility to incorporate active pharmaceutical ingredients into the orthopaedic devices for targeted drug delivery applications. Schilephake et al. demonstrated in vitro the controlled release of recombinant human bone morphogenic protein (rhBMP) from PLA implants since rhBMP has been shown to promote bone formation, and they concluded that the incorporation of rhBMP2 into PLA implants with subsequent slow release of biologically active growth factor was possible [72]. In another study the continuous release of insulin-like growth factor I (IGF-I) from PLA and PLGA was investigated in sheep bone defect model by Luginbuehl et al. It was reported that new bone formation was improved in the defects treated with IGF-I embedded PLA and PLGA compared to defects filled with IGF-I free PLA and PLGA [73]. Antibiotics have also delivered through PLA orthopaedic devices to treat osteomyelitis. Ramchandani & Robinson demonstrated this using PLGA implants containing ciprofloxacin hydrochloride. The prolonged release of ciprofloxacin was observed for a period ≥ six weeks [74]. Similarly, Liu et al. investigated PLGA impregnated with vancomycin in a rabbit model, and the release of vancomycin was measured over 55 days [75]. Cao et al. developed PLA and levofloxacin blended beads to treat osteomyelitis and detected the release of levofloxacin from PLA for up to 6 weeks [76].

Interestingly, PLA or PLA based bone fixation devices were reported in relation to bone tunnel enlargement following anterior cruciate ligament (ACL) reconstruction, which comprises widening of the tibial and femoral tunnels on imaging examinations produced sequentially after the operation [77]. Frosch et al. studied the clinic cases of ligament graft fixation with biodegradable interference screws, Milagro, which is made of 30% β-TCP (TriCalcium phosphate) and 70% PLGA (poly-lactic-co-glycolic acid) [78]. They reported that the degradation behaviour of Milagro was closely linked to the graft healing process, and Milagro cannot prevent the tunnel enlargement in the first 6 months but ingrowth of bone tissue in the screws reduced the tunnel volume significantly after 1 year. However, in another study carried out by Singhal et al., 19 patients were involved in tibial tunnel enlargement assessment after the implantation of biodegradable screws, which composed of poly-L-lactide and hydroxyapatite. It was reported that all patients undergoing degradation of this screw had increased tunnel expansion with average of 110% [79].

In summary, PLA has a long history of use in the orthopaedic field, and it has many advantages over traditional metallic orthopaedic implants. However, problems with the use of PLA have also been reported. These issues include the acidic degradation product and difficulties in adjusting the degradation rate of PLA. The degradation product induces an acidic environment, which will catalyse the further degradation and reduce pH value, causing adverse tissue reactions [80]. However, Liu et al. reported a less harmful acidic degradation of PLGA with the addition of titania nanoparticle [81]. Proper tissue restoration within a reasonable time was not allowed due to the slow degradation process of PLLA [82], [79], whereas prematurely failure of PLA inserts was reported due to early degradation introduced from internal stresses [63].

3.3 PLA coronary stents

Coronary heart disease is one of the leading diseases to cause death in the western world. One of the most common and effective medical interventions performed to treat CHD is the percutaneous coronary intervention (PCI), and coronary stent implantation is one form of PCI. The materials used for coronary stents are almost exclusively metals such as magnesium alloys, stainless steel, nitinol, cobalt chromium alloys. One major issue of metallic stents is ions leaching, which can be toxic to cells, or even carcinogenic. For example, 316L stainless steel and nitinol both c ontain large amount of nickel, and nickel has been reported to be potentially carcinogenic [83], [84].

Another major problem associated with metallic stents is restenosis, which is the reoccurrence of the blockage. Compared to bare metal stent (BMS), drug eluting stent (DES) has a much lower rate of restenosis [85], [86]. However, other complications related to DES were reported such as late stent thrombosis (LST) [87]. Farooq et al. concluded that underlying mechanisms of restenosis with DES could be divided into 4 main causes, namely, biological factors (resistance to antiproliferative drug, hypersensitivity reactions etc.), arterial factors (wall shear stress, vessel diameter, etc.), stent factors (polymer coating release kinetics, strut size, polymer disruption, peeling, cracking etc.) and implantation factors (in complete stent expansion, geographical miss etc.) [88]. Hence, there is an urgent need to address the issues that arise with metallic stents.

Biodegradable coronary stents, which degrade away after service without causing long-term body immune reactions, appear to be an ideal option to treat CHD. Several fully biodegradable stents are currently manufactured and their composition is presented in Table 4. PLLA has been utilized by 3 out of 5 manufactures from the table 4 because it is stronger than most of the biodegradable polymers to support the vessel and withstand the pressure from the vessel wall. What's more, PLA has a long history in stents industry as polymer coating and drug carrier for DES which helps to streamline regularity approval [89].

Table 4: Fully biodegradable scaffolds [90]

Stents	Manufacture	Material	Trials
ABSORB BVS	Abbott	PLLA	ABSORB A, B, Extend, Π
Igaki-Tamai	Kyoto Medical	PLLA	Igaki-Tamai
DESolve Nx	Elixir	PLLA	DESolve FIM, Nx
ReZolve	Reva	Tyrosine polycarbonate	RESORB, RESTORE
DREAMS	Biotronik	Magnesium alloy	BIOSOLVE-1

The Igaki-Tamai stent was the pioneering fully biodegradable stent based on PLLA scaffold and it is currently only used to treat peripheral arteries. 10-year data for 50 patients has shown that six months follow up performance was satisfactory with initial hyperplasia comparable to bare metal stents, and a four year follow up showed the stents degraded completely with no further hyperplasia development [91]. Biodegradable vascular scaffold (BVS) everolimus-eluting PLLA coronary stents are manufactured by Abbott, and zero stent thrombosis was published from a clinical trial of 130 patients [90]. These stents have been launched in India [92], and will be released in America for a large scale clinical trial [93].

Various fabrication methods of biodegradable stents have been investigated. The traditional method of laser machining used for metallic stents manufacturing can be used for polymeric stents as well. But the heat affected zone and solidification of molten material on cut edges can be problematic. A few laser machining methods have been investigated to fabricate biodegradable stents. Femtosecond laser was reported by Heublein et al. to fabricate biodegradable magnesium stents but high cost is an issue [94]. Excimer laser was reported by Barenghi et al. to fabricate biodegradable polypropylene fumarate stent [95]. Stepak et al. utilized CO2 laser and claimed that elements cut with CO2 Laser have better mechanical properties than those fabricated with excimer laser [96]. Apart from laser machining other fabrication methods include rapid prototyping [97], weft-knitting [98] and braiding technology [99].

In summary, despite the huge potential and interest in PLLA stents, clinical trial experience is limited. So far only two devices, Abbotts BVS and Kyoto Medical’s Igaki-Tamai stent, have completed clinical trial and have published the findings. Abbott has started enrolling patients for two larger BVS trials containing 1,500 patients in America and 225 hospitals across the country are taking part in this trial [93]. Biodegradable stents appear to offer a safe and effective option for PCI, but long term follow-up is still required.

3.4 PLA scaffolds in tissue engineering

Tissue engineering aims to restore, maintain, or improve tissue functions that are defective or have been lost by different pathological conditions, either by developing biological substitutes or by reconstructing tissues [100]. The current regenerative strategies for tissue loss and organ failure are based on transplantation [101]. However, transplant rejection and huge demand for organ donors remain a challenge. Tissue engineering has emerged as a promising alternative approach since late 1980s, as the organ reconstruction is completed with patients’ own cells.

To accomplish this, patients’ cells can be seeded into a three-dimensional porous scaffold, where the implanted cells can be supported and grow to produce functional replacement tissue. The ideal scaffolds should perform some or all of the following functions: 1): Promote cell-biomaterial interactions, cell adhesion, and extracellular matrix (ECM) deposition, 2): Permit sufficient transport of gases, nutrients, and regulatory factors to allow cell survival, proliferation, and differentiation, 3): Biodegrade at a controllable rate that approximates the rate of tissue regeneration under the culture conditions of interest, and 4): Provoke a minimal degree of inflammation or toxicity [102].

Polymeric scaffolds are drawing a great attention due to their unique properties such as high surface to volume ratio, high porosity with very small pore size, biodegradation, and mechanical property [100]. PLA is one of the most common synthetic polymers in tissue engineering as PLA-based scaffolds maintain their mechanical strength while providing specific cell-surface receptors during the tissue remodelling process [1]. Hence, polymeric scaffolds based on PLA have been investigated intensively. However, the hydrophobic nature of PLA limits its use in tissue engineering, since the surface hydrophilicity of scaffolds affects cell adhesion [1], [103], and cells adhesion strongly influence many of their functions, including growth, phagocytosis etc. [104]. To overcome the lack of bioactivity of PLA, blends of PLA and bioactive polymers are commonly used. Haaparanta et al. fabricated PLA/collagen hybrid scaffolds and reported a good cell viability and attachment on them [105]. Cui et al. modified PLLA scaffolds with chitosan and reported a significant improvement in cell proliferation as compared to unmodified PLLA scaffolds [103]. Similarly, Jiang et al. introduced chitosan to PLGA and reported that the chitosan/PLAGA scaffold was strong enough for bone tissue engineering applications, and the presence of chitosan on microsphere surfaces increased the alkaline phosphatase activity of the cell cultured on the composite scaffolds and up-regulated gene expression of alkaline phosphatase, osteopontin, and bone sialoprotein [106]. Later on they investigated the chitosan/PLGA scaffold in a rabbit ulnar critical-sized-defect model, and they reported that the chitosan/PLGA scaffold was able to guide bone formation, and a successful bridging of the critical-sized defect on the sides both adjacent to and away from the radius occurred [107]. Bone tissue engineering scaffolds require higher mechanical strength compared to other tissue engineering scaffolds, since an ideal bone scaffold should match bone properties and proper load bearing [108]. Therefore, intensive studies have been carried out in the field of reinforced PLA based scaffolds to support cell growth. Gomes et al. developed starch-PLA fibre-mesh (SPLA) scaffolds and reported that the SPLA scaffold exhibited adequate porosity and mechanical properties to support cell adhesion and proliferation and they also found that with increasing degradation time the diameter of SPLA fibres decreases significantly, consequently the porosity and the available space for cells and tissue ingrowth increased significantly, which promised a potential use in regenerating bone tissue [109]. Cheung et al. developed silk/PLA scaffolds which were tested to be strong enough to support cells [110]. Zhou et al. developed maleic anhydride grafted PLA-cellulose nanocrystals, which have shown good mechanical properties for supporting cell proliferation [111]. In summary, PLA-based scaffolds have been successfully tested on bladder tissue [112], liver tissue [113], vascular tissue [114], skin [115], and bone [116].

Several fabrication methods for PLA-based scaffolds have been reported. These include solvent-casting and porogens leaching [117], emulsion freeze drying [118], thermally induced phase separation [119], electrospinning [111], 3D printing [120], and gas foaming [121].

Biodegradable synthetic polymers such as PLA offer a number of advantages over other materials for developing scaffolds in tissue engineering, including the ability to tailor mechanical properties and degradation kinetics to suit various applications, and the ability to fabricate into various shapes with desired pore morphologic features [122], [108]. However, the degradation of PLA creates a local acidic environment causing adverse tissue response [108], which currently limits the clinical use of PLA-based scaffolds [123], [1]. Unfortunately, Regueros et al. reported an acute macrophage inflammatory response to PLA scaffolds in rat model study [124]. There are ongoing research efforts in improving the functionality of PLA and PLA based materials to further expand their applications in tissue engineering.

3.5 PLA in drug delivery systems

Drug delivery is the method or process of administering a pharmaceutical compound to achieve a therapeutic effect in humans or animals [125]. Traditional drug administration method is the repeated dosage every few hours or days, while the new approaches and strategies have been developed to control several parameters considered essential for enhancing the treatment performance such as rate, period of time and targeting of delivery [126]. The primary method of accomplishing long-term controlled release is through incorporating the pharmaceutical compound with biodegradable polymeric carriers [127]. Biodegradable polymers have been used as delivery tools for bioactive compounds due to good bioavailability, better encapsulation, control release and less toxic than conventional drug delivery system [128]. The main function of polymeric carriers is to transport drugs to the site of action and protect drugs from interacting with other molecules such as proteins, which could impair pharmaceutical action or even preventing the arrival of drugs at the desired location [129].

PLA and PLA-based polymers, such as PLGA are the most widely-used biodegradable polymers as drug carriers due to their excellent biocompatibility, biodegradability, mechanical strength, heat processability, solubility and permeability of many potent drugs, which are otherwise difficult to deliver orally [128]. They have been produced into various dosages forms including pellets, microcapsules, microparticles, nanoparticles, etc. [1]. PLA has a long degradation period and is suitable for long-term release applications, while PLGA has a higher degradation rate and much shorter degradation period than PLA, which makes PLGA suitable for short-term drug delivery [126]. In general, the degradation and the drug release rate of the biodegradable polymeric carriers can be accelerated by high hydrophilicity, increase in chemical interactions among the hydrolytic groups, less crystallinity and larger volume to surface ratio of the devices. Hence, for a short-term release requirement (up to 1 month), an amorphous polymer with high hydrophilicity is recommended, whereas, for a long-term release requirement (1 to 6 months), an amorphous polymer with high molecular weight should be considered. For a very long-term release requirement (more than 6 months), a semicrystalline polymer with high degree crystallinity such as PLA should be considered [130]. PLA and PLA based polymer such as PLGA have been increasingly investigated in the controlled delivery of proteins, vaccines, genes, antigens as well as growth factors [126], [1]. PLA/chitosan system has been reported to have a continuous release of anticancer drug, anthraquinone (AQ) [131] and DNA alkylating drugs [132]. Similarly, Gaspar et al. reported triblock poly(2-ethyl-2-oxazoline)-PLA-g-PEI (PEOz-PLA-g-PEI) with high efficiency for co-delivery minicircle DNA and doxorubicin [133]. Moreover, continuous release of triptorelin from PLA/PEG blend was reported by [134].

Apart from sustained release, targeted drug delivery is another important feature for modern drug delivery system. The encapsulated drug can be delivered specifically to a site of interest and released in a controlled manner, reducing drug side effects and enhancing therapeutic effects. Targeted therapy is of specific significance in cancer treatment, since some drug used to treat cancer such as camptothecin have low solubility in water and high toxicity. Hence, targeted drug-PLA conjugates act as a transport of drug and enhance its biodistribution while reducing the adverse systemic side effects [135]. Liu et al. has reported a successful molecularly targeted therapy using poly(ethylene glygol)-b-poly(d,l-lactide) (PEG-PLA) nanoparticles as carriers for siRNA to treat triple-negative breast cancer effectively [136]. Whereas, Yang et al. developed Folate-PEG-PLA carrying folate-modified curcumin loaded micelles (Cur-FPPs), which serve as a potential nanocarrier to improve the solubility and anti-cancer activity of Cur [137]. Fahmy et al. claimed that the major difficulty in targeted drug delivery of PLA-based polymer particle has been the lack of functional chemical groups on the aliphatic polyester backbone for linking to target ligands, which is also responsible for low encapsulation efficiency and high burst release of the encapsulated biomolecule within the first few hours or days [138]. To overcome this they engineered PLGA microparticles, which were surface modified with fatty acid, conjugated to avidin, and results showed an enhanced encapsulation efficiency and prolonged display of avidin over the course of several weeks. Zhao & Feng reported herceptin-conjugated docetaxel-loaded poly (lactide)-D-a-tocopheryl polyethylene glycol 1000 succinate copolymer (PLA-TPGS/TPGS-COOH) nanoparticles were effective for targeted delivery of anticancer drugs [139].

Developing new materials and preparation of responsive polymers with specific structure and chemical profile are the directions of the most recent research in drug delivery system. PLA is a responsive polymer, which can undergo abrupt changes that result from small variations in enviromental conditions, such as temeprature, pH, electric charges, ionic strength, electromagnetic radiation, UV/visible light, ioinc or metallic interaction or combinations. These stimuli can lead to different types of responses, such as degradation, drug release, dissolution/precipitation, swelling/collapsing [126]. Campardelli et al. successfully encapsulated near-infrared (NIR) sensitive hollow gold nanoshells (HGNs) with test molecule rhodamine into PLA carrier, the rapid heating of the PLA caused by NIR radiation enabled use of the PLA-HGNs composites as a phototriggered drug release system, and the release rate could be tuned by controlling the intensity of NIR exposition [140].

The medicine of the future is treated in a personalized way in accordance with the individual parameters, and new effective tailor-made drug delivery system is the direction of the development in this field [126]. PLA and PLA based polymers are widely utilized in drug delivery system and will expand their applications in the personalized treatment, since they have the advantage that they can be synthesized with specific properties for a given application.

3.6 PLA in other medical fields

PLA is used in the cosmetic industry. Atrophic scarring is a type of scar that is sunken and pitted. To treat this type of scar injectable agents such as collagen, hyaluronic acid and silicone have been used [141]. Sadove investigated injectable PLLA used for atrophic acne scarring treatment, and found that injectable PLLA is a good option for the correction of macular atrophic scarring with thin dermis, particularly when compared with other currently used injectable fillers for this indication, which have shorter duration of effect [142]. PLLA as a volumising filler has been reported to be used in replacement of deep tissue atrophy for human immunodeficiency virus (HIV) lipatrophy and atrophic acne scars [141].

PLA was also reported to be used in adhesive barrier applications. Welch et al. investigated PLA film as an adhesion barrier to posterior spinal scar formation and concluded that PLA adhesion barrier membranes was an effective treatment for reduction of posterior adhesions [143]. A biodegradable polymeric film composed of PLA and PEG developed by SyntheMed has been approved by the FDA. It is used as an adhesive barrier to prevent adhesions or interconnections between two opposing surfaces, specifically between the chest wall and the pericardium. Because as natural responses to injury, a great number of fibroblast cells can be released at the injury site and turn into dense adhesions. This PLA and PEG barrier film can effectively reduce the severity of post-operative cardiac adhesions [144].

In summary, despite of all the advantages of PLA in medical applications, there are still some challenges: 1) Difference in the degradation rate compared to the healing of surrounding tissue, which is a major challenge for PLA. When the degradation rate is faster than tissue regeneration, the defects will reoccur. Conversely, material left behind, when degradation is too slow, may interfere with tissue physiology [41]. 2) The degradation product of PLA is lactic acid, which is a relatively strong acid. The release of large volumes of lactic acid can lower the local pH level and possibly trigger an inflammation response [80], [108], [123], [1]. The ability of implant site to eliminate the PLA degradation products is the key factor in biocompatibility. 3) Sterilization is a challenge for PLA medical devices [41]. The sensitivity of PLA to hydrolysis does not allow the use of high temperature and high humidity. Hence, PLA devices cannot be sterilized by the traditional autoclave method [145]. PLA chemically reacts with ethylene oxide, so ethylene oxide (EtO) sterilization is not suitable. Radiation gamma sterilization at dry ice temperature is preferred, since radiation may induce degradation of PLA chains, temperature and dose condition should be closely controlled [146]. 4) PLA is considered to be hydrophobic, which affects cell adhesion and limits its application in related medical field [1].

4. PLA in Fibre/Textile Applications

For the past two decades, nylon, PET and polypropylene are the main synthetic polymers used for fibre/textile. But the concerns over heavily dependent on petroleum-based polymer and the current crisis in solid waste management have led the development of biodegradable materials fibre/textile.

Since the breakthrough in PLA manufacturing process, PLA has been widely used in domestic and commercial applications. Fibre/textile is one of the largest application areas for PLA [147]. Various types of PLA fibres can be produced by fibre spinning process, such as short-cut fibres, bulked continuous filaments, multifilaments, staple fibres and spun bond fabrics. PLA fibres/textile is not only biodegradable, but also highly functional. NatureWorks LLC compared PLA fibre with other common fibres and the results were listed in table 5. PLA fibre has great potential to replace the traditional fibre in textile applications due to its superior properties, such as hydrophilic feature, good dyeability, low flammability, antibacterial property and good weather resistance.

Table 5: Fibre properties comparison [148]

	Nylon 6	PET	PLA	cotton
Specific gravity	1.14	1.39	1.25	1.52
Moisture regain %	4.1	0.2-0.4	0.4-0.6	11
Flammability	Medium smoke, melt	High smoke, burn 6 min after flame removed	low smoke, burn 2 min after flame removed	burns
LOI%	20-40	20-22	26-35	17-19
Refractive index	1.52	1.54	1.35-1.45	1.52

4.1 Hydrophilicity

PLA is considered to be hydrophobic [1], which limits its use in tissue engineering and drug delivery applications, which often deal with hydrophilic molecules such as proteins. However, when it comes to fibre/textile applications, PLA fibre is more hydrophilic than many common fibre materials such as PET [149].

Hydrophilic feature of fibre/textile is desired to deliver comfortable feelings to users [150]. Many currently used fibre/textile has to undergo surface treatment to enhance their hydrophilicity, e.g., cetyltrimethylammonium bromide (CTAB) treated wool fibre [151], and “4DG” PET fibre with deep grooves on the fibre surface that provide capillary wicking [152]. However, PLA fibre/textile is naturally hydrophilic and feels very comfortable for users due to the excellent moisture transport [149]. The moisture regain of PLA is 0.4-0.6% [148], which is higher than other polyesters. Water molecules have access to the polar oxygen linkages in PLA molecules, which improves the wettability and the moisture transmission of the fibres, and allows the breathability of finished clothing. Hence, PLA fibre is a good option for clothing and personal belongings. PLA fibre/textile shows superior wicking performance, ability of spreading moisture by capillary action, compared to petroleum-based polymer fibre, which promises applications that require high liquid absorbance, such as workout clothing, diapers and wipes [153]. Actually, PLA wipes is one of the fastest growing application areas [147].

4.2 Good Dyeability

Dyeability is an important parameter in fibre applications. PLA fibre has very good dyeability and can be disperse-dyed using standard PET dyes and dyeing procedure [152].

Refractive index influences dyeing properties. PLA’s refractive index is 1.35-1.45, while PET’s refractive is 1.54 [148]. The lower refractive index of PLA causes a deeper, stronger and brighter shade of the disperse dyes obtained on PLA compared to that on PET at the same applied dye concentration [154], [155]. The optimum dyeing condition for dyeing PLA are 110°C for 30 minutes under acidic pH (pH = 5), whereas PET dyeing is normally carried out 20°C higher (130°C) under a more acidic condition (pH = 4) [156]. The lower processing temperature leads to a reduction in production cost of PLA compared to PET.

However, it has been reported that PLA fibre is thermally sensitive, and as such the strength of PLA fibres decreased at the dyeing temperature of 110°C [157], and colour fastness properties of disperse dyes on PLA are lower than those on PET due to thermal migration of the dye from PLA when subjected to heat [155].

4.3 Low Flammability

The limiting oxygen index (LOI), a common parameter for flammability, is defined as the minimum concentration of oxygen that will support flaming combustion of a material. A high LOI (i.e. greater than 21) is indicative of a less easily and less flammable material resisting to self-sustained burning. When a material has a LOI more than 32, this material is fire retarding. PLA has low flammability and shows good self-extinguishing characteristics [158]. The LOI of PLA is higher than many other fibres such as nylon and PET [148], [158], which means PLA’s flammability characteristics are better than fibres made from those materials. When PLA fibre burns, significantly less smoke is released than many other common fibres such as PET, hence visibility hazards of PLA fibres in a fire are reduced [152]. Therefore, PLA fibre/textile doesn’t need flame retardant treatment like other petroleum-based polymer fibres. PLA fabrics without any flame retardant treatment have already passed the US standard for the flammability of clothing textiles (16 CFR 1610), and have also achieved the standards specific for children’ sleepwear 16CFR 1615 and 16CFR 1616 [40]. The low flammability feature makes PLA fibres attractive for use in home/office furniture applications.

4.4 Antibacterial or Bacteriostatic Properties

Antibacterial or Bacteriostatic properties are unique feature of PLA fibre/textile distinguishing from other fibre materials. Lactic acid is a relatively strong organic acid and it exhibits antibacterial/antifungal properties. Mutsuga et al. investigated the migration of lactic acid, and the small amount of lactic acid migrating from PLA fibre may be responsible for the antibacterial property of PLA fibre [159].

Mochizuki investigated the antibacterial property of PLA fibres, and the number of bacteria in PLA fibres tested after incubation for 18 hours at 37°C decreased dramatically, while that in nylon fibres increased rapidly [158]. The antibacterial properties of PLA fibres make it an ideal polymer for use in the hygiene market, including towel and wipes. In fact, towels of 100%PLA fibres have a reputation that don’t generate bad smells after long-term use, which might be attributed to this antibacterial feature of PLA fibres [149].

4.5 Good Weather Resistance

Superior resistance to daylight, rainfall and UV is an attractive feature of PLA fibres for outdoor use [158]. PLA does not absorb light in the visible region of the spectrum, which leads to very low strength loss when exposed to ultraviolet light [40]. NatureWorks investigated burst strength, molecular weight and colour change of PLA, PET and acrylic fibres with exposure to UV light, and reported that PLA and acrylic had similar burst strength loss, while PET had the worst; PLA had the smallest change in colour, while acrylic had the greatest change in colour; PLA fibres remained unaffected through changing levels of UV light and were resistant to UV light , while the other two polymers had high absorption levels, consequently affected molecular weight and other properties [160]. Mochizuki carried out an accelerated weathering test and found that the weathering stability of PLA fibres was superior to that of PET fibres [149]. UV resistance property makes PLA fibres a good option for outdoor applications with a few years’ service requirement.

In summary, as an environmentally friendly polymer PLA has the potential to replace petroleum-polymer in some applications, such as clothing due to excellent moisture transport; towels and wipes due to wicking property; hygiene products due to antimicrobial feature; home/office furnishings due to low flammability and good UV resistance. However, PLA has played a limited role in the textile market due to relatively high prices, sensitivity to humidity and temperature, and poor abrasion resistance, which might limit it use in high-performance applications, such as ropes [152], [161]. Given the attractive properties of PLA and the development in green textile industry, PLA will become a very attractive polymer for the textile market [161].

5. PLA in film Packaging Applications

In the last decade, PLA has been developed for a wide range of primary packaging applications including oriented and flexible films [162]. Oriented PLA film can be manufactured by extrusion casting with drawing-induced crystallization, and since it can retain its transparency with improved reasonable strength, thermal and impact resistance, and elongation [163], it has been greatly utilized in packaging and protective film applications, such as bags, bottles, disposable beverage cups and cutlery.

However, Oriented PLA film is brittle, and tends to generate folding lines and then break when used as bags. Hence, brittleness is a major drawback of PLA film. Flexible PLA film that blended with plasticizers or other ductile materials can overcome this limit, but sacrifice some strength of PLA, and thermoforming can be used to manufacture un-oriented or flexible film [163]. It is reported that the fracture energy of PLA can be improved by blending with polycaprolactone (PCL), and the improvement is considered to be achieved by stress relaxation and energy dissipation mechanisms such as extensive multiple craze formation of continuous phase and creation of extended fibril structures of dispersed phase [27]. Al-Itry et al. reported that the brittleness of PLA can be reduced by blending with poly (butylene-adipate-co-terephthalate) (PBAT), but the blend of PLA/PBAT experienced a reduction in tensile modulus compared to PLA [164]. Furthermore, Hughes et al. reported that by adding acetonitrile the flexibility and thermal stability of PLA film can be improved [165]. Flexible PLA films are regularly used as eco-friendly compostable alternatives to LDPE and HDPE [166].

5.1 Barrier Properties

Gas, water vapour barrier properties are essential for packaging applications, since gas and water vapour can influence the shelf life of the packed products. Unfortunately, PLA film is a relatively poor barrier to water vapour with high water vapour transmission rates (WVTR). The WVTR of PLA film is three to five times higher than that of PET, LDPE, HDPE and oriented PS; while the oxygen barrier properties of PLA film is better than that of PS but not as good as that of PET [167]. Nevertheless, the high WVTR allows water evaporate easily, which provides a dry environment that is suitable to protect products from growing mold [168]. Suzuki& Ikada investigated the growth rates of common molds on PLA, PCL and polybutylene succinate film, and they found out that molds cannot grow easily on the surface of PLA film [41]. This antimicrobial/antifungal property allows PLA film to be an ideal material for fresh food packaging, such as bags for fresh vegetable, fruit and bread. Furthermore, the high transmission rates mean that PLA has a huge potential use in the cheese industry, as natural ripening, the most traditional ripening process, requires air-drying [169]. PLA film promotes this due to its high transmission rates, which allows cheese to remain dry in the natural ripening process while provides protection for cheese from external factors.

Much research has been carried out to improve the gas and water barrier properties of PLA film. Blending PLA with other biodegradable nanoparticles is the most frequently used approach. Arrieta et al. blended PLA with poly (hydroxybutyrate) (PHB) and cellulose nanocrystals (CNC), and found that PLA-PHB-CNC showed improved water resistance and reduced oxygen and UV light transmission [170]. Similarly, Pantani et al. blended PLA with ZnO nanoparticles, and observed PLA-ZnO film with improved barrier properties due to the increased tortuosity of the diffusive path of the penetrant molecules [171]. Bang & Kim utilized an alternative method to improve gas barrier properties, where inorganic silica was incorporated into PLA to develop an organic-inorganic hybrid materials using sol-gel technology [172]. It is reported that the gas barrier properties were substantially improved by the addition of silica. Among all the various modifications for PLA film barrier properties, it also needs to be pointed out that the thickness of film can influence the transmission rates, when the thickness of the film is increased, the transmission rates are decreased, which was demonstrated by Bedane et al. [173]. Hence, to meet application specific requirement of transmission rates, modifying the film thickness is also an option.

Despite PLA’s poor gas, water vapour barrier properties, it does have good taste and aroma barrier properties. The aroma compounds contain 4-12 carbon atoms and functional groups and the taste and aroma barrier is a combination of sorption into and permeation through the packaging material [174]. Obuchi &Ogawa reported that colorants and aroma compounds do not diffuse easily from foods into PLA film [163]. Auras et al. also carried out gravimetric sorption tests and compared ethyl acetate and d-limonene, the most common compounds, in PS, PP, LDPE, PET and PLA films, and they found that PLA was not likely to promote flavour loss [175]. Due to the good organic compound barrier properties PLA film has potential for use in packaging applications for cheese, butter, milk and juice.

5.2 Heat shrink Wrap Property

Shrink wrapping differentiates from conventional packaging in that the plastic film shrinks tightly over the intended item when enough heat is applied. It was invented by Global Wrap LLC in 1981 [176].) and considered as a smart wrapping technique. Since then shrink wrap, which serves as a tamper and safety seal, has been widely adopted in packaging applications, including bottles, yachts, and even buildings. The shrink wrapping property relies on a film's tendency to want to return to its unstressed state when heat is applied. The common materials used in shrink wrapping are oriented PS, PVC, and polyolefin such as LDPE [177], and the shrink temperatures are 130-140°C, 90-100°C and 108-115°C respectively (Alpha Wire 2009; Dean 2000). Oriented PLA film begins to shrink above 60°C with a shrinkage ratio of about 70%, which makes it an excellent alternative to the common shrink wrapping materials [163].

However, the "draw back" of the outer edges of the shrink films is undesirable, which has limited the applications of shrink films. What's more, blown film and casting are the two techniques used to manufacture PLA shrink films. The cast film is better suited for sleeves and wrapping applications than blow film, but PLA films manufactured by casting method exhibit excessive shrinkage in the machine direction, which substantially contributes to curling and limits their application. Recently, Plastic Suppliers Inc. has been granted a patent in PLA shrink films and methods of casting [178]. They improved the casting method and tenner manufacture, reported that the PLA films manufactured by this method exhibited less than 10% of shrinkage in the machine direction.

5.3 Dead-fold or Twist Retention Property

Dead-fold or twist retention property is the ability of film to retain the twist and stay wrapped rather than opening [179]. Aluminium foils have an excellent dead-fold measurement of 100%, which means aluminium foils don't spring back after been folded. Conventional polymer films such as polyethylene (PE) and PET can't reach that high level. PLA film exhibits fairly good deadfold or twist retention property [167]. Oriented PLA film shows better dead-fold properties than PE [163]. Because PLA film is stiffer and has much lower elongation than other plastic film, such as polyolefin, and as such wrinkles tend to permanently remain in the film [180]. The deadfold or twist retention property makes PLA film ideal for wrapping applications like candy wrap.

In summary, PLA film is transparent, relatively strong, and has good aroma barrier properties, which make PLA film an ideal packaging for fresh food, such as vegetable, fruit, and cheese. PLA film also has excellent wrapping properties, and is an ideal option for shrink wrapping and dead-fold wrapping. However, low resistance to oxygen and water vapour permeation of PLA films compared with conventional petroleum based polymers limit its applications for food and medical packaging. Furthermore, other problems that need to be addressed include brittleness, thermal stability, high processing costs and high noise level during processing due to the PLA stiffness and crystallinity [181]. Research in improving thermal stability of PLA has been carried out and Corbion Purac has developed a high heat PLA that can withstand temperature up to 180°C [182], this improvement enables PLA's applications to expand to areas such as hot water bottles and heat resistant fibres.

6. Summary

The increasing concern over waste disposal problems, global warming, environmental pollution and the depletion of petroleum resources has driven the increased use of PLA which is derived from renewable resources, such as corn and rice, and subsequently break down into water and carbon dioxide as a promising alternative to petroleum-based polymers. Its renewability, biodegradability, good biocompatibility and mechanical properties make PLA a promising material for use in various medical applications. Over the past few decades, PLA has been successfully use in biodegradable sutures, coating over stents, fully biodegradable stents, drug carrier in delivery systems, tissue scaffolds and orthopaedic applications. However, the drawbacks that limit its applications need to be addressed in future research, including difficulty to sterilize, poor hydrophilicity for cell adhesion, adjustment of degradation rates to meet the requirements of applications.

The recent capability to produce PLA at high quantities relatively cheaply has enlarged the applications of PLA to packaging, textile and other commercial applications. PLA fibres outperformed other common fibre materials such as nylon, PET, PP, cotton in terms of: 1). High wicking performance. 2). Good dyeability. 3). Self-extinguishing and low flammability characteristics. 4). Good UV resistance. 5). Antibacterial/antifungal feature. PLA film has been widely utilized in packaging and other commercial applications. The advantages of PLA film can be summarized into 4 points: 1). High water vapour transmission rates of PLA can maintain a dry environment and protect products from molding. 2). Good flavour and aroma barrier properties stop colorants and aroma compounds diffusing easily from foods into PLA film. 3). Good heat shrink wrap property 4). Superior dead-fold or twist retention properties for wrapping applications. However, there are still some problems in PLA fibre and film applications, including poor abrasion resistance, sensitive to humidity and temperature, brittleness, high processing costs and high noise levels during processing.

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