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Polylactic Acid (PLA) is a biodegradable polymer gaining popularity as a replacement for conventional plastics in different industrial sectors. However, PLA has inherent limitations and requires modifications to enhance its performance. This review article covers the different important aspects related to the PLA such as the synthesis route of PLA, biodegradation mechanism of PLA, properties of PLA, and applications of PLA in different sectors. The main focus of this review is to identify the different innovative copolymers, blends and composites of PLA for biomedical applications. Most important characteristics such as degradation behavior, biocompatibility and mechanical properties of these PLA-based biodegradable polymers were briefly discussed. This review indicates that the optimization of processing techniques and suitable selection of additives play an important role to achieve the desired properties of PLA. This review also discusses the issues associated to PLA-based materials for biomedical applications.

# 1 Introduction

Polyester-based biodegradable polymers have been used in variety of application such as pharmaceutical, orthopedics, cosmetics, food packaging, textile, electronics, and transportation [1–3]. These polymers exhibit better biodegradability, and better mechanical properties. To increase the use of these polymers in different engineering sectors there is need to overcome the issues associated with these polymers such as immunogenicity, low biodegradability, less antibacterial activity and less biocompatibility [4,5]. Further, to meet the required design criteria for different applications, it is important concern to improve the properties of these polymers.

Among the different polyester-based biodegradable polymers, polylactide or polylactic acid (PLA) is one of the most important

renewable source-based biodegradable polymers because it is adaptable, thermoplastic, biodegradable, biocompatible and has

Many review articles have been published in recent years on PLA synthesis and applications. Li et al. [23] focused on the applications and synthesis of different biodegradable materials especially PLA. Mehmood et al. [24] discussed the potential of PLA in different applications and trend of its demand in market. More et al. [25] discussed the different synthesis methods of PLA

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great mechanical qualities, excellent processability, optical clarity, and low cost [6–9]. It is produced through fermentation from renewable resources like sugar or maize starch [10–13]. Its tremendous properties, for example good biodegradability, biocompatibility, and easy processing make it best for biomedical applications [14,15]. PLA blends are used in tissue engineering, drug delivery, wound management, implants, and biomaterials developments [16–18]. In orthopedics, PLA composites are used for making screws, pins, plates, nails and wires [19,20]. In cardiovascular, PLA-based scaffolds or stents are used for coronary artery disease [21,22].

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and the role of different polymers for making the copolymers of PLA. Taib et al. [6] discussed the degradation mechanism and applications of PLA. Joseph et al. [26] discussed the potential of three-dimensional (3D) printing technologies for the production of PLA and its blends. Fernandez et al. [27] discussed the potential of 3D printing for the fabrication of PLA-based scaffolds. Swetha et al. [28] discussed the methods for the production of PLA from food waste by the process of fermentation. Dana et al. [29] discussed the synthesis techniques of PLA-based polymers and their applications. This review helps to choose the suitable technique for adjusting properties of PLA. Kour et al. [30] discussed the different additive manufacturing techniques such as electrospinning, and 3D printing for the fabrication of PLA scaffolds. The review of literature clearly showed that, most of the researchers focused on the fabrication techniques and applications of PLA-based materials. There is little interest in summarizing the innovative PLA-based materials especially composites of PLA.

The main focus of this review is to summarize the properties of different innovative PLA-based materials and to discuss their potential for biomedical applications. This review will help to identify the materials for making new-generation biomedical devices such as screws, plates, pins, scaffolds, etc. This review article describes that further research is necessary to optimize the design and processing of these PLA-based materials, as well as to evaluate their long-term biocompatibility and performance in animal and human body. Additionally, this review can help in the development of new PLA-based materials that address specific challenges associated with biomedical applications, such as infection control and tissue regeneration, which hold significant potential. Overall, the application of biodegradable materials in orthopedics has the potential to revolutionize treatment options, providing patients with safer and more sustainable solutions that improve their quality of life.

## 2 Synthesis of PLA

Lactic acid (LA) is a crucial component in the glycolytic energy cycle of living organisms, discovered in 1881 through fermented milk extraction [31,32]. As a hydroxy acid, it possesses an asymmetric carbon atom, resulting in optical isomers d-LA and 1-LA. d-LA is extracted from animal muscle, while 1-LA is obtained through fermentation. Commercially, LA is produced by fermenting sugars with bacteria, utilizing sources like glucose, maltose, starch, and lactose from potatoes and corn. Traditional fermentation methods involved the addition of calcium carbonate or calcium hydroxide, forming crude lactic acid and insoluble calcium sulfate [33]. Subsequent processes like dyeing, electrolysis, and ultrafiltration, followed by evaporation, crystallization, and acidification, produce purified lactic acid suitable for medical or food applications [34]. For large-scale industrial production, LA is produced via lactonitrile intermediates [35]. Each production route has its distinct set of steps and raw materials, impacting the overall cost and efficiency. However, chemical synthesis has drawbacks, such as the racemic nature of the product, comprising equal proportions of l-LA and d-LA, making it unsuitable for certain applications, particularly in the pharmaceutical industry [36].

The synthesis of PLA involves a multi-stage process commencing with the production of LA and concluding with polymerization, with lactide formation serving as an intermediary step [37]. Several polymerization methods, including azeotropic dehydration condensation (ADC), enzymatic polymerization, direct polycondensation (DPC), solid-state polycondensation, chain extension, and ring opening polymerization (ROP) can be employed to convert LA into PLA [38]. In the DPC method, LA undergoes dehydration into oligomers before undergoing polymerization into PLA. This necessitates moisture removal to prevent polymer degradation [7,39]. However, the elimination of water during LA condensation within the highly viscous polymer melt poses substantial challenges. DPC entails the use of solvents and catalysts to facilitate water removal under high vacuum and temperature conditions, resulting in the production of polymers with varying molecular weights. Direct synthesis of PLA without the need for catalysts, solvents, or initiators is attainable under elevated temperatures and vacuum conditions. The LA direct condensation process encompasses four distinct phases: dehydration, oligomerization, polycondensation, and PLA melt condensation. Notably, water elimination emerges as the rate-determining step during both the initial and final phases [6,40,41]. While this route holds the potential to yield high molecular weight PLA, it is not frequently employed on a large scale, primarily due to the rapid degradation of LA and competing lactide synthesis. The process of melt polycondensation, characterized by the transition from liquid to solid, facilitates the production of high molecular weight PLA by employing a chain extender, such as 1,6-hexamethylene diisocyanate [42]. ADC and ROP represent the most prevalent synthesis strategies, to achieve high purity, high molecular weight and optimal performance of PLA [43].

The synthesis process is shown in Fig. 1. The figure showed that PLA synthesis constitutes a multifaceted process involving LA production, purification, and polymerization. Multiple techniques, including polycondensation and ROP, can be harnessed to produce PLA with varying properties and molecular weights, necessitating rigorous purification and precise control of reaction conditions to ensure the production of high-quality PLA.

Condensation polymerization is considered cost-effective, but poses challenges to produce high molecular weight PLA. Coupling or esterifying cation-promoting agents are used for the production of long-chain molecules. However, this method has drawbacks such as unreacted chain-extending agents and impurities in the final polymer. ADC without chain extenders produces high molecular weight PLA. Effective parameters influencing polymerization and final molecular weight include solvent, catalyst, reaction temperature, and impurity level. Impurities from fermentation, such as methanol, ethanol, and acids, significantly affect final molecular weight. ROP, another polymerization technique, allows control of molecular weight despite requiring catalysts [44-46]. Factors like residence time, processing temperature, catalyst category, monomer type, and dand l-lactic acid ratio influence the process. High-purity lactide is crucial, and the procedure involves decompression, water removal, catalyst addition, resulting in lactide for polymerization. Polymerization yield, transesterification effect, and chain length

Direct Polycondensation Solid State Polycondensation Low molecular weight prepolymers 
$$\begin{array}{c} -H_2O \\ -H_2O \\$$

Fig. 1
Polymerization route of PLA. Modified and printed with the permission from [23].

can be regulated by adjusting time, temperature, and catalyst type, while impurities impact the final molecular weight.

## 3 Biodegradability of PLA

PLA undergoes biodegradation through a multi-step mechanism that involves chemical and microbial processes. Understanding this mechanism is crucial for managing the biodegradability of PLA-based materials in various applications. PLA degradation primarily occurs through alkaline and enzymatic hydrolysisinduced ester bond cleavage [47,48]. The ester bonds within PLA polymer chains are broken, resulting in the formation of carboxylic acids and alcohols as degradation product [49]. These shorter PLA units then become substrates for microorganisms. Microorganisms possess enzymes that can further degrade PLA. This microbial depolymerization process involves the action of extracellular and intracellular depolymerizing enzymes [49]. Shorter units of PLA produced by the action of extracellular enzymes further degraded into intracellular enzymes. The degradation mechanism of PLA through hydrolysis is shown in Fig. 2. PLA degrades into LA under acidic conditions through the activation of hydroxyl groups.

PLA degradation also occurs under aerobic and anaerobic processes [51]. Soil microorganisms, such as actinomycetes, bacteria, and fungi, are essential for efficient PLA degradation [52]. While PLA is biodegradable, its slow degradation rate is attributed to the molecule's rigid main chain and the presence

of methyl groups on its side chains [50]. In landfills, PLA degrades into low molecular weight polymer, which can either be decomposed by microbes or fragmented into microplastics. These microplastics enter the aquatic food chain, reaching higher trophic levels, including humans, through prey-predator interactions. The addition of enzymes or nutrients can accelerate the degradation of PLA in soil [48,53]. Bacterial activities in soil can stimulate the degradation of PLA [54]. So, combinations of enzymes, bacteria, and other nutrients are used to accelerate the degradation process of PLA in landfills [55]. Unlike in soil, PLA primarily undergoes hydrolysis in seawater, targeting the amorphous regions of the ester bonds within the polymer [56,57]. However, PLA degradation in seawater is notably slower due to the lower temperatures and fewer types of microorganisms capable of breaking down PLA. Thermal degradation is another significant pathway for PLA when subjected to high temperatures during processing. PLA's thermal decomposition temperature range falls between 320 °C and 420 °C. Under these conditions, thermal cracking occurs, leading to the production of propylene glycol esters, cyclic oligomers, and linear oligomers [58,59]. This thermal degradation mechanism is particularly relevant in industrial settings where PLA undergoes high-temperature processing.

Researchers have explored the degradation behavior of PLA in different environments. Gunti et al. [60] investigated the degradation behavior of PLA in different environments. Thermal results showed that the degradation of PLA was started at 322  $^{\circ}$ C

(a) 
$$CH_3 \cap CH_3 \cap CH_$$

Illustration of PLA degradation mechanisms (a) Back-biting reaction depicts depolymerization into lactide followed by hydrolysis or through the protonation activation of hydroxyl groups (b) Chain end scission occurs under acidic conditions. Modified and printed with the permission from [50].

and the degradation was completed in temperature range of 322-430 °C. The degradation of PLA in enzymatic environment was much faster as compared to the degradation in soil burial. Pelegrini et al. [61] evaluated the degradation of PLA in marine environment for 600 days. 2.5% weight loss was recorded after 60 days of exposure. The change in crystallinity of PLA due to the hydrolysis was started after the 15 days. The damage in amorphous segment was started after 45 days and the loss of integrity of PLA matrix was started after 100 days of exposure. The addition of starch into PLA promotes water absorption, disrupting PLA's crystal structure and hastening its degradation, albeit at a still relatively slow rate [62,63]. Natural fibers like jute or hemp, when added to PLA, can enhance its mechanical properties while retaining biodegradability [60,64]. Many fiberbased reinforcements are added in PLA matrix to improve the degradation behavior of PLA [48].

The degradation of PLA in vivo may involve plasma cells, lymphoid cells, eosinophils, macrophages, foreign body cells, mast cells, lymphocytes, histocytes, and fibroblasts. The tissue layer around the PLA-based device usually decreases after the

implantation. The PLA degradation inside the human or animal body occurs through hydrolysis of the ester-bond breakage. The tissue enzymes may be involved at the late stage of degradation process. The degradation process initiated due to the segregation between central core and surface that consists of water absorption accompanied by molecular weight decrease and ester bond cleavage. The diffusion of oligomers started from the thin surface of specimen due to the differentiation between the inner core and surface of implant, and allows solubilization in the aqueous medium. The degradation mechanism of PLA-based biodegradable device is shown in Fig. 3.

The degradation rate depends on the impurities, nonreacted monomers, temperature and pH. In addition to environmental factors, compounding PLA with other materials can affect its degradation. The degradation behavior of PLA-based device is investigated in vitro and in vivo before the clinical trial and use in human body. Li et al. [67] immersed the PLA samples in Kirkland's biocorrosion media for 4 weeks to investigate the degradation behavior of PLA. The gradual decrease in pH was observed for PLA. 1.15% mass loss in PLA sample was

Fig. 2

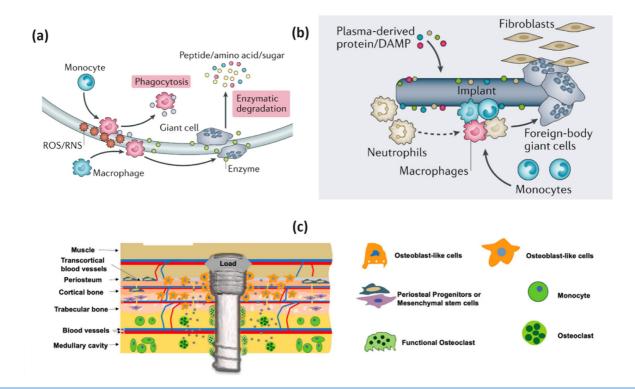


Fig. 3

Degradation mechanism of PLA-based biodegradable device (a) Degradation via enzyme and phagocytosis (b) Degradation of the biodegradable implant via proteins, fibroblasts, monocytes, blood cells (c) Degradation process of interference screw in bone tissue via osteoblast cells, osteoclast, monocytes, and stem cells. Reprinted with changes and permission from [65,66].

recorded after the 30 days immersion. The immersion of PLA in high temperature fluid decreases the pH, indicating higher degradation at higher temperature. Russias et al. [68] investigated the mechanical behavior of PLA after the immersion of PLA samples in salt and Hanks solution. The decrease in mechanical properties was observed after the immersion of PLA samples in vitro environment. Gogolewski et al. [69] investigated the degradation behavior of PLA implant in vivo and monitored the change in molecular weight and mass of PLA over the period of 6 months. The molecular weight of three PLA samples decreases 48, 19 and 6% over a period of 1 month; 56, 40 and 32% over a period of 3 months and 82, 56 and 82% over a period of 6 months. The results showed increase in degradation rate with decrease in molecular weight of parent material. The increase in crystallinity of PLA device at initial stage of degradation has been reported in literature [70]. This increase is attributed to chain scission in the amorphous regions of the polymer, which enhances the mobility of non-degraded chain segments, leading to their recrystallization. This process occurs alongside hydrolysis, which can degrade chains in the crystalline regions, potentially causing a decrease in crystallinity. However, there isn't a clear boundary between these two stages of degradation. Surronen et al. [71] investigated the degradation behavior of PLA plates in vivo and in vitro. In vivo, after the five years PLA samples were almost resorbed, but the particles of PLA were detected at the implantation site. Although the PLA plates were completely damaged, but they retained their shape at the end of five years

follow up. In vitro 52% mass-loss was recorded at the end of five years.

## 4 Properties of PLA

PLA exhibits excellent properties, including excellent gas barrier capabilities, elasticity, and biocompatibility, making it suitable for various applications [72–74]. Additionally, PLA exhibits thermoplasticity, allowing it to undergo reversible deformation under heat, and provides resistance to ultraviolet radiation, making it effective as a UV barrier [75,76]. Its hydrophobic nature further adds to its appeal, as it demonstrates resilience against water absorption. Furthermore, PLA offers a desirable level of rigidity, providing structural integrity for diverse uses [70]. The degradation, cytotoxicity, tensile strength and elastic modulus of PLA are important properties for designing any biomedical device [77–79]. Another important property that should be considered in any biomedical application is the recrystallization rate. PLA is completely soluble in chloroform and partially soluble in tetrahydrofuran and it is not soluble in water, alcohol, etc. [80,81]. The mechanical properties of most common PLA-based polymers such as PLA, poly-l-lactic acid (PLLA), and poly-d,l-lactic acid (PDLLA) are given in Table 1.

PLLA is considered a semicrystalline polymer and PDLLA is an amorphous polymer [82]. PLA consists of l-LA blocks therefore it is semicrystalline and its structural integrity is high [83]. If provided with high temperature it will show more mechanical strength. Among the polymeric variations, PLLA has

Mechanical properties of PLA [24].

Mechanical Parameter	PLA	PLLA	PDLLA
Melting temperature, ( °C)	150–162	170–200	Amorphous
Glass transition temperature (°C)	45-60	55-65	50-60
Ultimate tensile strength, (MPa)	21-60	15.5-150	27.6-50
Ultimate tensile strength, (MPa)	21-60	15.5-150	27.6-50
Tensile modulus (GPa)	0.35-0.5	2.7-4.14	1-3.45
Ultimate tensile strain (%)	2.5-6	3.0-10.0	2.0-10.0
Specific tensile modulus (kNm/g)	0.28-2.8	0.80	2.23-3.85

captured considerable attention from researchers. PLLA exhibits a crystallinity of approximately 37%, a melting temperature of 180 °C, and a glass transition temperature of 67 °C. This specific variation showcases the potential for tailoring PLA to meet the demands of various applications, highlighting the ongoing efforts to optimize its properties for broader usability [84]. PLLA is a comparatively rigid polymer and is more transparent [85]. The tensile strength of PLLA is 45–71 MPa. Moreover, if PLLA is blended with poly-d-lactic acid (PDLA) then the PLLA melting and heat deflection temperature can be increased.

The degradation of PLA is in the range between six months to two years and depends upon molecular weight [86,87]. The mechanical properties would variate according to degradation time. It should be noted here that PLA's physical and mechanical properties are affected by polymer crystallinity. However, despite these commendable properties, PLA is not without challenges. It tends to be brittle under specific conditions and requires elevated temperatures for crystallization, contributing to a slower manufacturing process [88,89]. The presence of ester bonds in its linear structure results in low resistance and hydrophilicity, limiting its application in certain contexts [90]. Recognizing these limitations, there is a collective effort to pool resources and enhance PLA's properties without compromising its overall performance. The required properties of PLA for different applications are given in Table 2. One avenue for addressing these challenges involves the use of specific catalysts designed for syndiotactic or isotactic materials [91-93]. Tacticity, or the arrangement of monomers in the polymer chain, plays a crucial role in determining PLA's properties. In a syndiotactic arrangement, side groups are situated alternately on the main chain, while an isotactic arrangement places side groups on the same side as the main chain [94-96]. The presence of second or ternary phases in PLA also influence the properties of PLA [97,98]. Understanding and manipulating tacticity contribute to managing properties such as crystallinity. Gug et al. [99] introduced the tris(nonylphenyl) phosphate stabilizer to improve the mechanical properties and thermal stability of PLA. Zhang et al. [100] introduced the light stabilizer (Irganox 1010 and Chimassorb2020) to improve the weathering resistance of PLA and its blend with polybutylene adipate terephthalate (PBAT). Better weathering resistance was achieved with the addition of Chimassorb2020 as compared to Irganox 1010. Przybytek et al. [101] used epoxydized soybean oil as a reactive modifier to improve the ductility of PLA without compromising degradation.

Effect of different catalysts on the properties of PLA [29].

Material	Weight fraction (wt.%)	Temperature ( °C)	M <sub>w</sub>
Mg	0.5	160	2100
Zn	0.5	160	35,000
Al	0.5	160	5400
Sn	0.5	160	240,000
ZnO	0.62	160	20,000
TiO <sub>2</sub>	0.83	160	1600
SnO	0.57	130	230,000
$H_2SO_4$	2.5	130	65,000
$H_3PO_4$	2.5	160	1300
SnCl <sub>2</sub>	0.80	130	230,000
$ZnCl_2$	1.04	160	18,000
$Fe_2(LA)_3$	1.70	160	27,000
$Mn(AcO)_2$	1.57	160	19,000
Ni(AcO) <sub>2</sub>	1.51	160	140,000
Ti(BuO) <sub>4</sub>	3.55	130	8000
$Y(OA)_3$	2.92	160	20,000
$Cu(OA)_2$	2.75	160	1900
$(Bu)_2SnO$	1.05	130	130,000
Nafian-H	2.00	160	4000
PTSA	2.5	130	1,000,000

Akrami et al. [75] prepared the novel compatibilizer based on maleic anhydride grafted polyethylene glycol grafted starch to improve the adhesion and biodegradability. The results showed negligible effect of compatibilizer on the biodegradability of PLA. Gallego et al. [102] introduced the new compatibilizers by grafting polyethylene with maleic anhydride and by adding hydroxyl group into polyethylene. The improvement in toughness and loss in thermal stability was reported with the addition of compatibilizers. Zhan et al. [103] investigated the effect of triglycidyl isocyanurate as a compatibilizer on the mechanical properties of PLA. The results showed the increase in flexural and tensile strengths of PLA with the addition of compatibilizer. Nim et al. [104] converted the commercial PLA resin into medium-sized lactate oligomers via alcohol-acidolysis reaction. The results confirm the high compatibility of PLA for drug delivery applications. In conclusion, while PLA possesses exceptional characteristics, ongoing research and collaborative initiatives aim to overcome its limitations and unlock its full potential for diverse applications. Many materials can be used as a catalyst to improve the properties of PLA. These materials and their effect on the molecular weight of PLA are summarized in Table 2.

#### 5 Applications of PLA

PLA serves a diverse range of applications in the chemical, biomedical, pharmaceutical, cosmetic, and textile industries. PLA is approved by food and drug administration (FDA) and is used in pharmaceutical industry for drug delivery, sutures and particle systems. Destefano et al. [105] summarized the use of PLA in healthcare and modern medicines. The potential of PLA for tissue engineering, cardiovascular, epithelial cells regeneration, drug carriers, cancer therapy, tendon and skin regeneration, dental implants, orthopedics, antibacterial packaging, surgical tools, respiratory equipments, and modern healthcare equipment has been briefly discussed. Lassalle et al. [106] discussed the

methods for the fabrication of PLA-based drug carrier. PLA and its copolymers with polyethylene glycol (PEG) and glycolic acid exhibit suitable properties to fabricate different kind of drug carriers. Tyler et al. [107] identified the copolymers of PLA for drug delivery carriers and discussed the issues associated to these PLA-based materials. PLA-based drug carriers can be used to carry leposomes, dendrimers, polymeric nanoparticles, micelles, and toxic anti-tumor drugs. Mundel et al. [108] indicated that PLA is one of the most important biomaterial for micelles and copolymer of PLA with PEG can be used effectively as drug carrier for cancertumor targeting. Vert et al. [109] investigated the performance of PLA-based bioresorbable stent in human body by monitoring the adhesion of proteins (globulins, fibrinogen, and albumin). The hemocompatibility of surfaces in contact with blood was improved by using PLA stent strut.

PLA's anti-acne, anti-aging properties and control release of active ingredients for skin make it suitable for cosmetic sector [110–112]. Rancan et al. [113] investigated the suitability of PLAbased drug delivery carriers for dermatotherapy. The nanoparticles of PLA were loaded with fluorescent dyes and the release of dyes from PLA particles was investigated. The results showed that PLA-based carriers can be used ideally for sebaceous gland and hair follicle targeting. Nam et al. [112] prepared the microbeads for cosmetics by melt electrospraying. PLA microbeads exhibit promising properties for cosmetics as compared to non-degradable microbeads. Hajleh et al. [114] discussed the different techniques such as precipitation-based methods, emulsion-based methods, microfluidic, in-situ forming and direct compositing methods for the preparation of micro and nanoparticles of PLA for cosmetics. Connolly et al. [111] tested the PLA-based materials for cosmetic packaging. No dermal hazard was reported during the testing with skin cells.

PLA is most widely used 3D printing material and is used in plastic industry for making various engineering parts. Trivedi et al. [115] concluded that PLA-based materials can be used as alternatives to produce low-cost sustainable engineering products. Gere et al. [116] investigated the recyclability of bottle-grade PLA. The results showed that the use of compatibilzers is effective to increase the thermal stability of PLA for making bottles. Roy et al. [117] investigated the effect of different printing parameters to fabricate the PLA-based engineering parts via 3D printing. Tamburini et al. [118] compared the performance of PLA bottles with polyethylene terephthalate (PET) bottles for drinking water. The results showed that PLA bottles are safe for drinking hot water and soap. Knoch et al. [119] modified the PLA from hydrophilic to hydrophobic to create exclusion nets for uniform supply of pesticide in crops. PLA nets showed molecular absorption for active ingredient incorporation due to the increase in phytosanitary effect of PLA textile. Franca et al. [120] prepared the PLA-based films for agricultural mulch. Such PLA-based films are cost effective and environmental friendly. Mochizuki et al. [121] discussed the features of PLA for nonwoven fabrics. The promising weathering stability of PLA, thermal properties, hydrolysis resistance and electrical properties showed the applicability of PLA fibers in commercial applications. Yang et al. [122] produced PLA/ramie woven for automotive industry. Gong et al. [123] prepared PLA-based hybrid nano-generator

Electronic skin device. This PLA-based device can be used to turnon and off the light emitting diode and generate the output signals. Many other researchers reported the use of PLA-based materials for many more applications. The use of PLA in different sectors is summarized in Table 3

PLA-based materials have the potential to fabricate the different prosthetics and orthopedic devices [134,135]. In implants, PLA-based materials are used to make the screws, plates and other devices for bone applications [136]. PLA is used to make degradable scaffolds, and stents to treat coronary arterial diseases. Different biomedical devices made by PLA-based materials are listed in Table 4. PLA's gradual degradation ensures the long-term retention of mechanical strength, which is crucial for applications like orthopedic screws and plates [137]. Furthermore, PLA's interaction with host tissue is modulated by its surface properties. Modification techniques such as surface roughening or functionalization can enhance cell adhesion, improving osseointegration in orthopedic and dental implants.

# 6 Copolymers and blends of PLA

Blending PLA with other polymers is a common technique aimed at enhancing its toughness and overall performance. Different types of copolymers and blends are prepared to improve properties and to target the required characteristics in the product which are summarized in the Table 5. PLA blends and composites offers improved properties as compared to pure PLA and extensively used in variety of applications. PLA blends find extensive use in packaging applications due to their biocompatibility and stress-handling capabilities during storage and transportation. The blend of PLA with polyhydroxybutyrate (PHB) in presence of LA oligomer as a plasticizer, prove suitable for packaging due to the recycling capability [179-181], while PLA blend with polyhydroxyalkanoates (PHA) demonstrate potential for compostable materials in agriculture [182]. PLA/PHA blend can be used in food packaging due to its antimicrobial properties and dielectric properties [183-186]. The blend of PLA with polybutylene succinate (PBS) exhibit improved thermal characteristics for food packaging applications [187,188]. The addition of different elements, such as oxidized olein, further improves the properties.

For biomedical applications, PLA is blended with PEG, polyglycolic acid (PGA), poly-l-glycolic acid (PLGA), poly(3hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), PDLA, and other polymers. The inclusion of PGA in PLA, such as PLA/PGA, allows tailoring of degradation rates to specific implant needs. For instance, PLA-based ocular implants, often blended with polyvinylpyrrolidone (PVP), exhibit improved drug release kinetics with increasing PVP content, ensuring precise therapeutic dosing in ophthalmic applications [189–191]. Such as the addition of polyethylene vinyl acetate (PEVA) mixture is particularly effective in treating periodontal disease due to the controlled release rate which correlates with the blend ratio [192,193]. Blend of PLA with polycaprolactone (PCL) offer extended applicability as a shape memory blend due to PCL's slower degradation rate compared to PLA [194,195]. Sing et al. [196] prepared the composites of PLA with chitosan and studied the failure behavior of these composites. Jeong et al. [197] prepared PLA/PCL films

Table 3
Use of PLA in different sectors.

Name of industry	Use	Advantages	Disadvantages	Ref.
Pharmaceutical	Control drug carriers	Improves the replenishing of fluids	Can change the shape of red blood	[107]
industry	Tablets		cells	
	Intravascular			
	Surgical sutures			
Cosmetic industry	Moisturizers	Improves antibacterial activity	Cause skin irritation	[111,124
	Exfoliating agent	Used for hydration and lightening		
	Lightening agent	of skin		
	Anti-aging	Alpha-hydroxy acid removes dead		
	Anti-acne	cells		
Plastic	PLLA	Used in polymerization,	Low molecular weight	[125]
	PDLA	dehydration, reduction.	_	
	PDLLA	decarboxylation and self-		
		esterification processes.		
Agriculture	Vegetation nets	Biodegradability	More acidic	
	Mulch films	Ecological nature	No nutrient	[126,127
	Seeding pots	Hydrophobic nature	Change the pH of soil	• ,
Textile	Sanitary napkins	Biodegradability	Low recyclability	
	Household wipes	Great durability	, ,	
	Disposable garments	Fire resistance		
	UV-resistant fabrics	Phytosanitary effect		
	Upholstery	,		
Transportation	Impacts shields of car	Plasticization to increase ductility	Low thermal stability	[128]
•	Components of car doors	High tensile strength	Low toughness	[129]
	Engine covers	High stiffness	Brittle behavior	
	Instrument panels	3	Low impact resistance	
Electronics	Porous membrane in water	Dielectric properties	High melt flow rate	
	purification and air filtration system		<b>3</b>	
Food Packaging	Cups	Biodegradability	Low heat resistance	[130,131
3 3	Overwraps	Easy processing	Low recyclability	• ,
	Containers	3	Compostable but not fast enough	
	Bottles		p	
	Compostable bags			
Orthopedics	Sutures	Resorbability	Low mechanical properties	[132,133
- p	Screws	Easy processing	Low biocompatibility	, . 30
	Pins, plates	, ,		
	Scaffolds			

by using the solution casting technique. Dichloromethane was used as solvent with PLA as a based material. PCL was added about 1wt%, 3wt%, 5wt%, and 7wt% of PLA in fusion films and then characterized for the identification of the impact of PCL on the mechanical properties without reimbursing the biodegradability of PLA. PLA/3PCL films displayed the highest elastic modulus 54 MPa along with elongation at a break of 8.84%. However, PLA/7PCL elongation at break achieve maximum inclined with 9.92% value while the modulus of elasticity decreased up to 37 MPa. Cytotoxicity test revealed that cell viability was more than 100%. These PLA/PCL films possessed promising mechanical properties for clinical trials. Moreover, PLA/PCL has the potential to use in tissue engineering [198,199]. Abdullah et al. [200] investigated the impact of incorporating cellulose nano-fibrils into PLA/PBS composite scaffolds for vascular tissue engineering. By varying the ratios of PLA and PBS, they determined that an equal ratio produced scaffolds with optimal properties and bioactivity. The researchers successfully developed composite scaffolds by reinforcing the PLA/PBS matrix with cellulose fibrils, leading to significant

improvements in overall performance. These scaffolds exhibited a uniform fibrous structure with desirable dimensions, improved degradation rate, and mechanical properties comparable to native tissue. Moreover, the PLA/PBS/cellulose fibrils scaffolds exhibit improved proliferation of cells. Li et al. [201] prepared the novel copolymer of PLLA, trimethylene carbonate (TMC), and glycolic acid (GA). The blend ratios of PLLA, GA, and TMC were 95:5:0, 94:5:1, 92:5:3, and 90:5:5. A vascular stent of resultant novel copolymer with a bionic surface and a shish kebab structure was prepared using the solid state drawing (SSD) process. The mechanical strength of a copolymer (with blend ratio 95:5:0) was lower (45.4 MPa) to meet the required design criteria for vascular device due to the lower molecular weight (less than  $2.5 \times 10^4$  g/mole). The novel copolymer (with blend ratio 90:5:5) exhibits tensile strength of 333 MPa due the addition of TMC. This significant increase in strength is attributed to the change in structure from spherulites to shish kebab. The biocompatibility results in L929 cells culture showed that the novel copolymer (with blend ratio 90:5:5) exhibits best cell viability.

Table 4
PLA-based devices in bone applications.

Biomaterial	Device name (Manufacturer)	Use	Response (Degradation time)	Ref.
PLA	EUROSCREW PLA	Fixation of soft tissue and	Retain shape and exhibit stability	[66,138]
	(Teknimed, France)	tendon-bone grafts	for 8 to 10 month after the	
			implantation	
DLLA	District	District with a ball and wells and amount	(2 years)	
PLLA	Biotrak (Acumed, USA)	Biotrak pins, helical nails, and screw Facilitate fixation in lower and	predictable degradation (5 years)	[139]
	(Acumed, OSA)	upper extremities	(5 years)	[139]
	BioScrew	Ensures graft fixation	Slow and gradual degradation	[140–142]
	(ConMed, USA)		(7 years)	
	Fixorb-MX	Fixation of maxillofacial fractures	High anchoring strength (3 years)	[143,144]
	(Takiron, Japan)			
	Bio-TransFix	ACL reconstruction set (pins, screw,	Does not lose strength over 52	[145–147]
	(Arthrex, USA)	wires etc.)	weeks (over 3 years)	
	GRAND FIX	Grand Fix fixation devices such as	Offers similar properties to the bone	[148,149]
	(Gunze, Japan)	plates and screws are used for	(3 years)	
		osteosynthesis and osteotomy operation.		
	lgaki-Tamai	Coronory stent used to expand the	Safe and effective performance in	[150,151]
	(Kyoto Medical, Japan)	stenotic portion of blood vessesIs	human coronary arteries	[:50/:5:]
		·	(2 to 3 years)	
	Absorb GT1	Coronary vasular scaffold system	Resorbed by the body	[152]
	(Abbott USA)	used in patients with ischemic	(3 years)	
		disease		
	DESolve	Novolimus eluting coronary scaffold	Similar to a de novo vessel.	[153–155]
	(Elixir Medical, USA)	system used for coronary artery	(1 to 2 years)	
	ArterioSorb	disease to restore blood flow Cardiovasular scaffold to treate	Degrades completely when the	[156 157]
	(Arterius, UK)	coronary artery disease	healing is complete (2 years)	[156,157]
	Mirage Microfiber Sirolimus-Eluting	Used to treat coronary artery	Exhibit novel mechanical properties	[158,159]
	(Manali Cardiology, Singapore)	disease	(1.5 years)	[:50,:55]
	Firesorb	Used in patients with obstructive	No-device-related thrombotic	[160,161]
	(MicroPort Medical, China)	coronary artherosclerotic heart	events occur after the implantation	
		disease.	(3 years)	
	MeRes100	Vascular scaffold to treat coronary	Ensures early endotheialization (3	[162,163]
	(Meril Life, India)	artery disease	years)	
	NeoVas	Coronary stent for artery disease	Inhibit the proliferation (3 years)	[164]
	(Lepu Medical, China) Xinsorb	Coronary stent for artery disease	Biodegradable rapsmycin eluting	[165–171]
	(HUAAN Biotechnology, China)	Colonally stellt for altery disease	stent (2 to 3 years)	[103-171]
PDLA	Sysorb Bioresorbable Interference	Offers secure juxtaarticular fixation	Altraumatic, blunt thread ensure	[172,173]
	Screw	<b>,</b>	ideal force transmission and	[,]
	(Sysorb, Switzerland)		prevents injury to graft (1.5 years)	
	Contour Meniscus Arrow	Used in suture-type fixation cases	Begins to degrade in 4 to 6 months	[174–176]
	(ConMed, USA)		(1.5 to 2 years)	
PDLLA	SonicWeld Rx	Provide stable fixation in the cranial	Degraded in controlled manner	[173–176]
	(KLS Martin, Germany)	region and eliminate the need for	(2 to 2.5 years)	
	ADT DDC	second surgery.	Foot and controlled decreated as	[177 170]
	ART BRS (Arterial Remodeling Technologies,	Used in porcine coronary artery model	Fast and controlled degradation (0.5 to 1.5 years)	[177,178]
	France)	model	(0.5 to 1.5 years)	

Blending PLA with natural fibers, derived from renewable plant sources, offers numerous advantages while being environmentally friendly. These natural fibers can enhance the performance of PLA-based materials and are biodegradable, posing no harm to the environment [202]. Starch, a widespread biomass filler found in various plant tissues, can be used to improve PLA's properties [203–205]. To make starch thermoplastic, it is essential to break its crystalline structure. This process results in thermoplastic

starch. However, starch is hydrophilic, while PLA is somewhat hydrophobic, making direct blending challenging. Oligo(LA)-grafted starch (OLA-g-starch) acts as a compatible additive for PLA blend with thermoplastic (TPS) [206]. By adding OLA-g-starch, the TPS phase is dispersed more uniformly, enhancing the compatibility between PLA and TPS. This addition improves ductility, melt flow, gas barrier properties, and thermal stability. Waste materials like wood leachate (WL), a byproduct from

Table 5
Summary of results on different type of PLA-based copolymers and blends.

Ref.	Matrix material	Filler material	Fabrication method	Biocompatibility	Degradation results	Mechanical results
[200]	PLA (50:50)	poly (butylene succinate) (PBS)	Electrospinning	MTT assay at 14 days showed 70.59% increase in cell proliferation as compared to Pure PLA	Enzymatic hydrolysis results showed slower but gradual biodegradation. Approx. 30% of weight loss in 14 days.	1.65 times increased Tensile strength
[219]	PLA	Starch (60:40)	Extrusion	Not Reported	Not Reported	Tensile strength – 42 MPa Modulus – 3230 MPa Elongation – 2% Modulus increases while tensile strength and elongation decreases.
[220,221]	PLA	PGA 75:25	Electrospinning	Improved cell adhesion and osteoblast regeneration	increased degradation rate	Improved tensile and flexural strength
[222–224]	PLA	PBAT (10 wt.%)	Solution casting Electrospinning	EG improves the biocompatibility and help for cell proliferation and oxygenation	Decreases the biodegradability	Tensile strength reduces but elongation increases
[225]	PLA	Chitosan 2.5 to 10 php	Melt compounding	Less cell recognition sites but good for wound healing.	Facilitate PLA biodegradation	55%a and 60% and in elongation and tensile strength at 2.5 php sample and brittleness increases with further addition of chitosan
[226–229]	PLA	PCL 80:20	3D printing Electrospinning	allowed good cell adhesion on neat and foamed PLA/PCL blends	Reabsorbing of Degradation products. Blends are less hydrophobic and have less resistance to traction	A decrease in displacement flexural strength. Improvement in compression and torsion strength
[230]	PLA	Polypropylene 50:50	Solution casting	Electrically stimulate the proliferation, cell growth and cell adhesion in electroactive sites	Decreases the biodegradability	Modulus and Tensile strength was increased while elongation was decreased
[231]	PLA	Cellulose	Grafting	Wound healing properties were improved	thermal stability and hydrophilic properties were reduced	38.24%, and 484% increase intear strength and elongation
[232,233]	PLA	Lignin 1 to 10%	Melt extrusion	Enhanced antioxidant activity, and steady biocompatibility	Help in decomposition	Small change in Young's modulus and tensile strength of the PLA matrix
[234]	PLLA	10% PGA – 5% PDLA (85:10:5)	Delta Resorbable Screw by Stryker, USA	No inflammation or bone tissues damage.	Gradual degradation, Degraded in 8 to 13 month	Attractive strength and contourability. Retain 75% of its initial strength at 12 weeks of the implantation.
[235]	PLLA	PLGA 18%	LactoSorb RapidFlap by Zimmer Biomet, USA	Low incidence of infection and inflammation	Degraded in 12 to 18 months	Retain 70% of its initial strength at 8 weeks of the implantation.
[66]	PLLA	PGA 15%	RapidSorb Orthomesh by DePuy Synthes, USA	No inflammatory complication	Degraded in 12 months	Retains 85% of its initial bending strength after 8 weeks
[236]	PLLA	PHBV 60%	Melt Extrusion	Not Reported	Degraded faster than pure PHBV	Reduced brittleness as compared to pure PLLA
[237]	PLLA	PDLLA and Trimethylene carbonate	Inion Hexalon Screw by Inion, Finland	Exhibit no inflammation	Degraded completely in 2 years	PLLA provides high strength, PDLLA and TMC provides required ductility and degradation.  Retain strength for 12 weeks and gradual loss of strength after 12 weeks.

fiberboard production, can also be utilized by extracting its solid components for blending with PLA. The lignin, phenol, and tannin in wood leachate (WL) can contribute to adhesive, antibacterial, and mechanical properties of PLA composites.

PLA/PCL blend finds applications in electronics, toys and mobile phones. In energy storage applications, a blend of 70 wt.% PLA with PHB shows promise for gel polymer electrolytes in Li-ion batteries, offering high conductivity, and electrochemical stability. Blends like PLA/PEVA/carbon back exhibit potential for semiconductor-based materials due to their exceptional electrical properties. PLA's durability is improved by incorporating polycarbonate (PC). Blends with poly-methyl-methacrylate (PMMA) or acrylonitrile butadiene styrene (ABS), demonstrate improved durability as compared to pure PLA. Moreover, PLA/PC and PLA/ABS blends are emerging environmentally friendly alternatives for automotive and electronic applications [207,208]. Practical applications, such as Samsung's use of a 60 wt% PC and 40 wt% PLA blend for mobile phone casings, showcase the feasibility of PLA blends in electronic devices [24]. Organizations like PEGA Design & Engineering successfully apply PLA in electronics, blending recycled medicalgrade PC with PLA for environmentally friendly materials comparable to novel mid-grade PC. PLA bends have the potential to use as a shape-memory polymer. Researchers have developed a PLA-based thermoplastic elastomer (PLAE) by combining PLA with PCL and introducing a polyurethane (PU) structure. PLAE, known for its softness and toughness, can be blended with PLA to create PLA-based shape memory materials with impressive shape memory and recovery characteristics. PLA blends with polyolefins like polypropylene (PP) and polyethylene (PE) offer durable solutions for furniture and the automotive industry, with the combination of PP and PLA exhibiting exceptional barrier properties suitable for medical product packaging [209-211].

One approach involves combining PLA with Acrylonitrilebutadiene-styrene (ABS), along with a compatibilizer. The addition of calcium carbonate (CaCO<sub>3</sub>) has been particularly effective in improving compatibility, thermal stability, and mechanical properties of the composites [212]. PBS, known for its thermal resistance and mechanical properties, can be used alone to reinforce PLA. However, PBS and PLA are both hydrophobic materials with non-polar surfaces. To improve interfacial compatibility, bulking agents have been employed. The resulting PLA/PBS/straw powder composites demonstrated optimal mechanical properties when the straw content was less than 5% [213]. Polypropylene carbonate (PPC), an aliphatic polycarbonate, can enhance the energy absorption capabilities and toughness of PLA while addressing PPC's thermal stability issues. Blending PPC with PLA results in partially compatible blends, but modifications using tert-butyldimethylchlorosilane, curcumin, ethylacetate, halloysite nanotubes, polyvinyl alcohol, and alkali lignin have improved their compatibility [214–218]. This modification, in turn, has led to optimized barrier and mechanical properties in packaging films.

Despite the potential of PLA, challenges remain for widespread PLA adoption, with ongoing efforts to enhance biodegradability and recyclability. Blending PLA with other biodegradable materials holds promise for improving its properties, provided

the challenge of maintaining solution viscosity is addressed. The focus on biodegradability and recyclability aligns with the growing emphasis on sustainable solutions. PLA's applicability extends to wide-surface products, overcoming brittleness and stickiness challenges through innovative blends. In summary, blending PLA with polymers and natural fibers offers a wide range of possibilities for enhancing its properties while promoting sustainability and reducing environmental impact.

## 7 Composites of PLA

PLA-based composites exhibit improved properties as compared to PLA copolymers and used in several applications. PLA is often combined with other materials to enhance its quality and properties. Cytocompatibility, the compatibility of these materials with living cells, is a critical factor when evaluating biomaterials for tissue engineering applications. In recent years, there has been a growing interest in incorporating nanoparticles into PLA to create advanced nanocomposites. PLA composites are gaining importance for biomedical applications. A variety of composites have been fabricated in recent years. Other inorganic reinforcements such as metals [238,239], metal oxides and carbonbased materials are also used to enhance the mechanical properties of PLA. Metal-based reinforcements such as Mg, Zr, Ca, and Zn, and metal oxide-based reinforcements such as MgO, TiO2, ZnO, SiO<sub>2</sub>, and CaO have also been used for improving the properties of PLA. The incorporation of carbon-based nanomaterials, such as carbon nanotubes (CNTs) or graphene, into PLA composites have shown several significant effects on the properties of the resulting material. These nanomaterials have shown promise in biomedical applications, particularly in improving the performance of PLA-based materials. These advanced materials hold promise in addressing specific requirements and advancing medical treatments.

## 7.1 Calcium-phosphate-based reinforcements

Calcium-phosphate-based materials have higher compatibility and bio-activity and structural similarities to the bone, as well as high bio-restorability [240-243]. Calciumphosphate-based reinforcements such as hydroxyapatite (HA) and tricalcium phosphate (TCP) have been incorporated into PLAbased composites for improving the mechanical and bioactivity properties of these PLA-based materials. Calcium-phosphatebased materials are the most widely used materials for the preparation of PLA composites even on the commercial scale [244-248]. The results on different biomedical devices made of PLA-based materials and calcium-phosphate-based materials are summarized in Table 6. TCP is better in terms of absorption than HA and has low strength. Several compounds lately are employed for bone and implants. Most recently, a variety of PLA composites have been developed [249,250]. These composites exhibit improved biocompatibility and mechanical properties [251-257]. PLA/HA, PLA/PCL/HA, and PLA/chitosan scaffolds have been developed in recent years [135,258,259]. Rad et al. [260] fabricated the scaffold of PDLLA and  $\beta$ -TCP utilizing a 3D printing technique with 40%  $\beta$ -TCP and 60% PDLLA. Then, the created portrayed were tested for their mechanical properties to compare their properties with real bone construction. The

Table 6

Summary of results on different commercial PLA-based devices.

Ref.	Matrix material	Filler material	Device Name	Manufacturer Name	Results/Features
[264]	PLA	TCP	Bio-INTRAFIX screw	DePuy Synthes, USA	Enough stiffness and strength No instability, swelling or pain was reported
[265–269]	PLLA	HA 25%	Biosteon screw and pins	Stryker, USA	HA prevents the premature degradation.  New bone formation confirms high biocompatibility.
[270]	PLDLA	β-TCP 30%	ComposiTCP Suture anchors	Zimmer Biomet, USA	$\beta$ -TCP decreases the inflammatory response in vivo. Exhibit 267 N fixation strength.
[271]	PLA	β-TCP 30%	EUROSCREW TCP	Teknimed, France	$\beta$ -TCP promotes bone growth and maintain neutral pH by buffer effect. Degraded in 2 years
[272,273]	PLA	<i>β-</i> TCP 30%	FastThread Interference Screw	Arthrex, USA	22% degradation without losing strength, 98% degradation in 3 years.
[274,275]	PLLA	HA 40%	OSTEOTRANS-MX plate, screw and mesh	Takiron, Japan	Bioresorbable and High strength
[276,277]	PLDLA	β-TCP 30%	LIGAFIX 30 screws	Anstem Medical, South Africa	Exhibit good mechanical properties and no inflammatory reaction, completely degraded in 2 to 3 years
[278–280]	PLDLA	$\beta$ -TCP 245	GENESYS Matryx	ConMed, USA	$\beta$ -TCP promotes bone growth and increase strength.
[281,282]	PLGA	β-TCP 30%	MILAGRO ADVANCE screw	DePuy Synthes, USA	90% degradation within 12 months, Resorb completely within 3 years
[277]	PLDLA	β-TCP 30%	Translig	Anstem Medical, SouthAfrica	No inflammatory reaction and strong fexation
[283]	65% PLGA	20% calciumsulfate and 15% $β$ -TCP	BIOSURE REGENESORB	Smith & Nephew, UK	Replaced by bone within 3 to 24 months

preparation of PDLLA/ $\beta$ -TCP composite was carried out using the solution casting method. Associations among PDLLA and TCP brought about superior compressive strength and elastic modulus of the composite. A biocompatibility test of the prepared scaffold was carried out showing satisfying results for its usage in bone generation engineering. Different types of PLGA materials are used for orthopedic applications [249,250]. In comparison with PLGA, PLGA/HA blends show good mechanical characteristics and biocompatibility [251–257].

Calcium phosphate, bioactive glass, HA, and TCP are also added with inorganic ingredients to improve mechanical strengths [238,239]. Owji et al. [261] investigated the incorporation of calcium phosphate into printable PLA for reconstructing craniofacial defects. Light-curable methacrylate-based polymers were explored as potential materials for bone repair, offering the ideal properties for this purpose and compatibility with 3D printing technology. The research involved the synthesis of a specific polymer (CSMA) and the fabrication of discs using a digital printing method. The study assessed various aspects, including the flow behavior of the polymer with different calcium phosphate-based additions, remineralization potential, in vitro cell culture, and ex-ovo angiogenic response. Consequently, the findings suggest that such polymeric systems offer promising features for designing 3D printed scaffolds

tailored to maxillofacial defect reconstruction without the need for calcium phosphate inclusion.

3D printing technologies are used for the fabrication of PLA/HA or PLA/TCP composites. Wang et al. [262] used the 3D printing using FDM technology to fabricate scaffolds for bone defects. The scaffolds were composed of PLA and n-HA. The study involved optimizing the composite scaffold through mechanical testing, and in vitro biocompatibility assessments using bone marrow mesenchymal stem cells. Subsequently, the researchers established a rabbit model to evaluate the osteogenic potential of composite scaffolds in vivo. The results demonstrated the high printability of the proposed PLA/n-HA composites, with tunable mechanical property based on the fraction ofn-HA components. Moreover, the cytotoxicity and osteogenic properties of the printed scaffolds surpassed those of pure PLA scaffolds. Harb et al. [263] prepared the 3D printing filaments made of PLA and  $\beta$ -TCP by melt extrusion to print 3D porous scaffolds. Approximate 20% improved in crystallization degree was recorded for PLA/TCP samples as compared to pure PLA. The tensile results showed that the elastic modulus of composite scaffold was improved from 73 MPa to 83 MPa. The cell viability results in osteobalst and mecenchymal cells showed that PLA/TCP composites exhibit improved cell viability as compared to pure PLA.

#### 7.2 Metal-based reinforcements

Various metal-based reinforcements are used to improve the properties of PLA. Various scientists used Mg for the fabrication of PLA composites. PLA/Mg composites, have demonstrated superior biological and mechanical properties compared to pure PLA scaffolds, enhancing bone formation. The incorporation of Mg micro-particles into the PLA matrix alters its mechanical properties, with a weaker binding between PLA and Mg particles. The release of Mg particles into saline affects pH levels, which can influence bone formation. Osteoclasts are sensitive to pH changes, and a slightly alkaline pH is crucial for bone formation.  $Mg^{2+}$  plays a role in osteoblast growth and bone formation. Optimal composite formulations exhibit pH values favorable for osteogenesis. Molecular mechanisms suggest that Mg<sup>2+</sup> enhances osteoblast activity and bone formation through various pathways. However, excessively high Mg<sup>2+</sup> concentrations may be toxic to osteoblasts. The release rate of Mg<sup>2+</sup> from composites is linear, and higher Mg particle ratios promote cell migration. In vivo studies confirm enhanced bone formation around PLA/Mg implants without affecting serum Mg<sup>2+</sup> concentration. Zhao et al. [284] prepared the PLA/Mg composite by solution casting and investigated the biomineralization and degradation behavior of these composites. Magnesium particles with 2 and 5% concentrations were selected as reinforcements in the PLA-based composite. In vitro, the immersion test was used to check the pH behavior and for vitro cell biocompatibility, mouse osteoblast cells were used to check the biocompatibility of prepared samples. SEM results revealed the uniform distribution of Mg in composite. The crystallinity of PLA was decreased due to the addition of PLA. The degradation test exposed that Mg particles neutralize the acidic behavior of PLA; hence it might be possible that the degradation of PLA is controlled by the percentage of Mg particles. The degradation tests showed the decrease in molecular weight of composites as compared to pure PLA. The study demonstrates that the incorporation of Mg into PLA improves the mechanical strength and promotes cell proliferation due to its osteoconductivity and biodegradability. The results of the study are presented in Fig. 4. The results in figure clearly indicate that the PLA/Mg composites exhibit improved cell viability as compared to pure PLA.

Yu et al. [285] prepared the PLLA/Mg composites by injection molding. First the acid-washed Mg powder was put in silane coupling agent 3-(Trimethoxysilyl) propyl methacrylate for surface modification of Mg particles. Propylamine and cyclohexane were used as the auxiliary materials for the fabrication of PLLA/Mg composites by injection molding. Rod samples with different diameters were prepared and tested under degradation and mechanical testing. The results of the study showed that the Mg/PLLA composites had good biocompatibility and cell viability, indicating their potential for use in orthopaedic implants. The mechanical properties of the composites were also found to be suitable for use in load-bearing applications, with the Young's modulus of the composites being lower than that of pure Mg. Li et al. [286] processed PLA/Mg composite by using a laminating method, then investigated the impact of the Mg on the mechanical properties and degradation behavior of PLA. 10% and 20% volume fractions of Mg wires were used for the preparation of composites. Prepared samples were then characterized for tensile and degradation testing. The result presented that due to the incorporation of Mg wires pH of PLA decrease down, however, mechanical properties like strength and modulus of 20% volume fraction showed maximum increment. The behavior of nanocomposites differs in vitro testing affected by the type of external loading (external and internal). Zhang et al. [287] investigated the mechanical and biocompatible behavior of PLA/Zn-Li biodegradable composites with traces of Ag and Mg. The preparation of samples was carried out by the casting process. Zn-Li-Ag alloy exhibits promising elongation at the break while Zn-Li-Mg characterized the optimal tensile properties. In vitro degradation tests were carried out in Ringer solution for 35 days. PLA/Zn-Li-Mg composite showed a maximum corrosion resistance rate. PLA/Zn-Li-Ag composites exhibit capable mechanical, biocompatible behavior for biomedical applications.

Many researchers focused on the modification microstructure and nanostructure of Mg reinforcements for PLA. Li et al. [286] performed a study on PLA-based biocomposite, reinforced with Mg alloy wires, designed for bone fixation implants. They investigated how the content of magnesium wires and different load modes influenced the degradation behavior of the composite and its components. The results showed that the presence of Mg wires in the composite slowed down the decrease in pH resulting from PLA degradation. Additionally, a higher fraction of Mg wires in the PLA led to a reduction in the degradation rate of the Mg wires themselves. Dynamic loading significantly accelerated the mechanical deterioration of the specimens. After 30 days of immersion, the retention in strength was lower under dynamic load conditions compared to no load conditions, indicating that dynamic load helped mitigate the degradation of Mg wires by enhancing the removal of acidic products from the composite through convective transport. Cai et al. [288] prepared the PLA/Mg-2 Zn composites by hot press and hot drawn method. First the Mg-2 Zn wires were wounded around Al plate and covered with solution of PLA and dichloride. Then the PLA laminae were stacked with Mg-2 Zn wires. The laminae were placed in a mold for hot press at 165 °C for 20 min and cold down to 80 °C for hot drawn. Further, the effect of number of passes of hot drawn and hot press was studied.

Many other metals such as Ti, Cu etc. have been used to improve the mechanical properties of PLA. Lee et al. [289] employed a fused filament fabrication method for the preparation of PLA/Ti composite scaffolds. The composites were characterized to check the effect of Ti on the mechanical properties and biocompatibility of PLA. Compressive test results revealed that the incorporation of 5-10 wt.% of Ti increased the compressive properties of PLA, but the trend for higher concentrations was different. The tensile modulus of PLA amplified for 5-15% of titanium incorporation, but other properties decreased within this concentration of Ti. Integration of Ti enhanced the vitro biocompatibility in terms of the underlying connection, expansion, and separation of preosteoblast cells. Barczewski et al. [290] investigated the impact of incorporating copper slag (CS) into a PLA matrix for the production of composite materials using rotational molding technology. The inclusion of copper slag (CS) into the PLA matrix

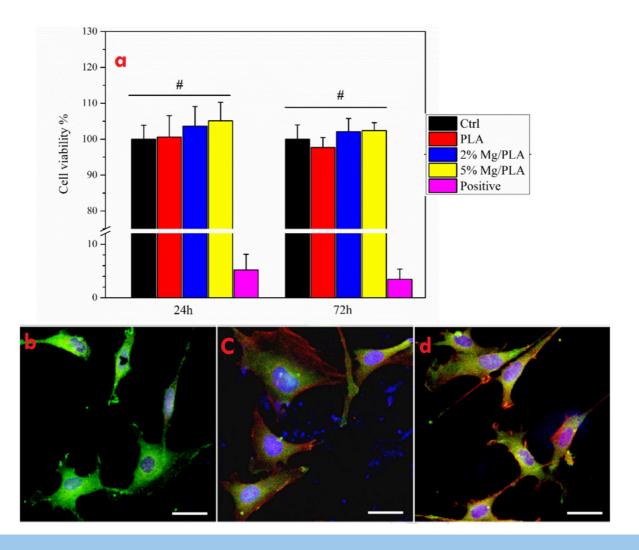


Fig. 4

Cell viability test results and corresponding images of confocal microscopy showing different cells such as actin nuclei (blue), vinculin(green) and filament (red) (a) Cell viability (%) after 24 hr and 72 hr (b) Confocal microscopy image of PLA, (c) Confocal microscopy image of PLA/2Mg and (d) confocal microscopy image of PLA/5Mg. Reprinted with changes and permission from [284].

for rotational molding technology led to several positive effects. It resulted in composite materials with improved stiffness and hardness while maintaining good adhesion between PLA and CS. Additionally, CS concentrations up to 20 wt% did not negatively impact the structural integrity of the composites, making them promising for various applications where enhanced mechanical properties are desired. Kottasmy et al. [291] focused on the development of PLA/Cu composites using FDM 3D printing. Mehbob et al. [292] performed a numerical analysis on PGA/Ti bone plates using 3D printing. The study found that the effective Young's moduli varied over time.

The results of the different studies showed that biodegradable metals such as Mg, Fe, Zn, Zr, Ca etc. are more suitable reinforcements for biomedical applications. Jiang et al. [293] investigated the additive manufacturing of biodegradable scaffolds for bone defects using PLA as the matrix reinforced with two different Fe-based particles: 316 L stainless steel and pure Fe. Employing fused filament fabrication (FFF), the researchers optimized printing parameters to achieve scaffolds with accurate

pore dimensions. The results demonstrated that the PLA/Fe and PLA/316 L scaffolds exhibited improved compressive and flexural modulus, compressive strength, and compressive fatigue resistance upon the addition of iron-based powders. The PLA/Iron scaffold, in particular, displayed higher in-vitro degradation, and enhanced cytocompatibility compared to PLA/316 L. This suggests that PLA/iron composite scaffolds hold considerable promise for bone defects.

## 7.3 Metal-oxide-based reinforcements

Metal oxide-based reinforcements such as MgO, TiO<sub>2</sub>, ZnO, SiO<sub>2</sub>, and CaO have also been used for improving the properties of PLA. Among these ZnO showed high applicability for the fabrication of PLA composites with improved mechanical, degradable and antibacterial properties. PLA/ZnO composites, combining PLA and ZnO nanoparticles, show immense potential for biomedical applications but confront several critical challenges. Boro et al. [294] prepared PLA/ZnO nanocomposites through solvent casting and investigated the effects of ZnO nanoflowers fraction on the

performance of PLA. Two types of PLA nanocomposites were synthesized with two different types of ZnO nanofillers: nanorods and nanoflowers. FE-SEM images confirmed the morphology of the ZnO flower-like structure. The tensile test results showed that PLA/0.5ZnO samples exhibit high tensile strength approximately 32.75 MPa as compared to pure PLA. The results of elastic modulus values of prepared nanocomposite samples showed that PLA/0.5ZnO showed a maximum value of 912 MPa. Elongation at break (%) results showed the maximum rise for the PLA/0.5ZnO. Its maximum value was recorded at approximately 4.8%. The increase in the concentration of ZnO nanofiller from 0.5 wt.% in PLA decreased the mechanical properties. Dispersion of nanofiller in the PLA played a vital role in the limitation of physical properties.

The nanocomposites containing ZnO nanoflowers exhibited better dispersion of the nanofiller in the PLA matrix, resulting in improved mechanical properties compared to those containing ZnO nanorods. It was also found that the sonochemical method used to synthesize the nanocomposites led to the formation of smaller ZnO nanoparticles, which enhanced the interaction between the nanofiller and the PLA matrix, further improving the physical properties of the nanocomposites. These composites exhibit improved mechanical, antimicrobial and antibacterial properties as compared to pure PLA. Heydari et al. [295] prepared the PLA/ZnO composites by solution casting methods. Two types of essential oils including Mentha piperita L. and Zataria multiflora L. were used to improve the interaction between PLA and ZnO. The results showed that the incorporation of ZnO nanoparticles and essential oils into the PLA matrix improved the mechanical properties of the bionanocomposites. The addition of ZnO enhanced the mechanical properties up to 9.93%, and elastic modulus up o 10.31%, but a decrement was noticed in elongation at break. The antibacterial activity, tensile and thermal properties were improved with the addition of nanoparticles. Restrepo et al. [296] fabricated PLA/ZnO composites by high melt processing. Comparative studies were conducted to investigate the effect of ZnO nanoparticles coated with polyvinyl alcohol (PVA) and uncoated ZnO. Polyvinyl alcohol was used as a stabilizing agent. A tensile test was performed using UTM. The mechanical properties were enhanced due to the incorporation of ZnO nanoparticles in PLA. The chosen concentration of ZnO was 1 wt.%, 3 wt.%, and 5 wt.% in PLA for both coated and uncoated nanoparticles. Due to the incorporation of ZnO ductile behavior of PLA was changed into brittle. No significant changes in Young's Modulus of PLA/ZnO nanocomposite films were observed as compared to neat PLA. Stress-strain curves showed no substantial variations in the values of tensile strength of PLA/nZnO film as compared to neat PLA films. The results of the study showed that the addition of PVA to the PLA matrix improved the dispersion of the ZnO nanoparticles in the nanocomposites, resulting in enhanced mechanical and thermal properties. Swaroop et al. [297] fabricated PLA/MgO nanocomposite films by melt processing and improved their mechanical properties. Prepared films were characterized in terms of mechanical properties and surface morphology. FE-SEM, FTIR, and Tensile Testing were used for characterizations. Films were prepared with 1%, 2%, and 3% concentrations of MgO in PLA. FE-SEM analysis illustrated that neat PLA film

possessed a smooth and uniform surface, while a rough surface was observed due to the incorporation of MgO. Tensile testing revealed that young's modulus of PLA boost up to 26%, and tensile strength up to 22% by the addition of 2% nanoparticles of MgO. An increase in elastic modulus emerged as nano MgO particles determine the movement of the PLA chain resulting in the expansion of stiffness (elastic modulus). Upgrading of tensile strength was noticed due to effective stress transmission between PLA and nano MgO particles. The 2% of MgO elongation at break was increased up to 181% as compared to pure PLA film. FTIR analysis demonstrated that no new type of bond formation has arisen between the functional group of PLA and nanoparticles. The barrier properties of the nanocomposite films increased with increasing MgO nanoparticle content. Zhang et al. [298] employed a solution casting technique for the preparation of PLA/nZnO composites. SEM was performed to check the surface morphology of prepared samples. Images revealed the homogenous dispersion of ZnO nanoparticles in the PLA matrix layer. Images exemplified that PLA/nZnO layer is well spread on paper, resulting in a smooth surface of prepared samples.

Lizundia et al. [299] fabricated PLLA/ZnO nanocomposite films by using the solvent precipitation method with chloroform as solvent. ZnO nanoparticle concentrations ranging from 0.25wt% to 5wt% of PLLA were used for film preparation. A tensile test was performed according to ASTM standards. The tesile modulus was improved for the 1 wt.% nanocomposite with growth in brittleness. ZnO played a crucial role in both structural recreation and mechanical properties of the nanocomposite. Tang et al. [300] processed PLA/ZnO nanocomposites by solvent evaporation method. The films were characterized to determine the change in mechanical properties and surface morphology. Different fractions such as 0wt%, 1wt%, 3wt%, 5wt%,7wt%,9wt%, and 15wt% of ZnO were added for the nanocomposite films formation. FTIR spectra of PLA/ZnO nanocomposite films displayed similar absorption bands to pure PLA (PLA-0) as shown in Fig. 1. PLA/7ZnO (PLA-7) and PLA/9ZnO (PLA-9) showed variation as compared to PLA spectra. Tensile testing results revealed that Tensile strength increased from PLA-1 to PLA-7 but dropped down drastically for the nanocomposites containing a high concentration of ZnO. Elastic modulus values show an increment from PLA-1 to PLA-7 and then a decrement for PLA-9 and PLA-15 as compared to PLA-0. Elongation at break displayed a decline from PLA-1 to PLA-7, which means the ductile behavior of PLA became fragile. But for PLA-9 and PLA-15 ductility of PLA becomes limited. SEM analysis concluded that by adding a more concentration of ZnO in PLA surface became coarse due to the heterogeneous distribution of nanoparticles. Pantani et al. [301] prepared PLA/ZnO nanocomposite films by melt compounding in a twin extruder. Nanorod like the structure of zinc oxide was used in film formation. 0.5, 1, 2, and 3% concentrations of ZnO were chosen for composite making. These films were then characterized for mechanical properties, and surface morphology. A tensile test was performed on ambient temperature to evaluate mechanical properties. Elastic modulus got significantly enhanced by the incorporation of ZnO as compared to pure PLA. Maximum elastic modulus was noted for PLA/2ZnO nanocomposite. Decline behavior was observed for the tensile stress in yield as compared to pure PLA. TEM images confirmed the shape of zinc oxide which was exactly nanorod-like. Nonato et al. [302] conducted a study on nanocomposites of PLA/ZnO nanofibers for potential medical applications, focusing on their antimicrobial effect, thermal behavior, and mechanical performance under cyclic stress. The study suggests that PLA/ZnO nanocomposites have potential for use in bone implants due to their antimicrobial activity and fatigue resistance.

Akshaykranth et al. [303] prepared the PLA/ZnO composites by a solution casting and studied the antibacterial activity of the prepared composites. The surface elemental and morphology composition of three distinct films, namely pure PLA (Film A), PLA/ZnO composites (Film B), and PLA/ZnO nanorods (Film C), provides valuable insights into the structural and chemical characteristics of these materials. Film A, composed of pure PLA, exhibited a remarkably smooth surface, indicative of a uniform and relatively featureless texture. SEM images of PLA filmsis shown in Fig. 5 (a to g). In Film A, consisting of pure PLA, the EDS spectrum revealed only carbon and oxygen elemental peaks, consistent with the chemical formula of PLA (C<sub>3</sub>H<sub>4</sub>O<sub>2</sub>). Notably, hydrogen, a low atomic weight element, was not detected in the spectrum, likely due to instrument sensitivity limitations. Conversely, Film B, the PLA/ZnO blend, displayed a minor atomic percentage of zinc (7.52%) in the EDS spectrum. This presence of zinc can be attributed to the ZnO powder particles dispersed within the film matrix. Intriguingly, in Film C, which featured PLA/ZnO nanorods, the EDS spectrum exhibited a significantly higher atomic percentage of zinc (36.78%) compared to Film B. This substantial increase in zinc content is primarily attributed to the extensive growth of ZnO nanorods on the film's surface, coupled with the presence of ZnO particles within the PLA film's structure. The results of different antibacterial studies are presented in Fig. 5g.

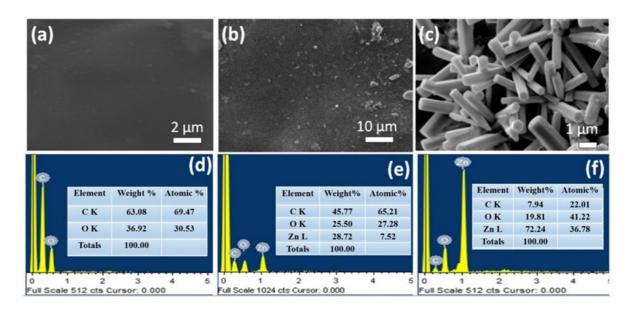
Agglomeration and uneven dispersion of ZnO nanoparticles within PLA matrices are common issues, particularly at higher filler loadings, which can hinder their antibacterial effectiveness. The weak interfacial bonding between PLA and ZnO due to surface functional groups like -OH affects mechanical and barrier properties, especially tensile strength. Moreover, PLA-ZnO nanocomposites are susceptible to thermal degradation, even below their glass transition temperature, primarily at elevated ZnO loadings, which can compromise their integrity. To tackle these challenges, various strategies have been proposed. The masterbatch technique involves a two-step process to create PLA-ZnO nanocomposites, reducing thermal exposure to PLA and enhancing ZnO dispersion. Surface treatments of ZnO nanoparticles, particularly with silane, have shown promise, acting as coupling agents, improving dispersion, and protecting PLA from hydrolysis. Other surface treatments, such as using PVA or in-situ aminolysis reactions, have also exhibited positive effects. Additionally, additives and processing approaches play a vital role in optimizing PLA-ZnO nanocomposites for various applications. Thermal stabilizers, oligomeric chain extenders, nucleating agents, and plasticizers are introduced to enhance thermal stability, processability, crystallinity, and mechanical properties. Surface location of ZnO nanoparticles, electrospinning, electrospraying, and growth

of ZnO on other fillers offer versatile methods to improve interfacial interactions and tailor properties. Additionally, engineering the surface properties of these nanocomposites offers a promising route to enhancing therapeutic effects and conferring antibacterial properties without solely relying on escalating ZnO concentrations. These advances underscore the potential of PLA/ZnO composites as a promising and safer option for various biomedical applications.

#### 7.4 Carbon-based reinforcements

Carbon-based nanoparticles such as graphene oxide (GO), graphene nanoplateletes (GNP), carbon nanotubes (CNT) etc. have showed outstanding properties. Therefore many researchers used these nanoparticles as a reinforcement into PLA to improve the properties of PLA. Wang et al. [304] prepared PLA/CNT composites by emulsion and masterbatch blending. First the CNTs and PLA were dispersed to develop water/oil interface. Regenerated cellulose (RC) was used as a mediator to achieve the uniform dispersion of CNTs in water. Then the prepared masterbatch was dispersed in a PLA by melt blending. This study demonstrates that the use of functionalized CNTs and a two-step dispersion approach leads to a significant increase in electrical conductivity while maintaining the desirable mechanical and thermal properties of PLA. The study also highlights the importance of surface functionalization of CNTs to improve their dispersion in the PLA matrix. The succinic anhydride treatment functionalizes the CNTs, making them more hydrophilic and reactive to the PLA matrix. The twostep dispersion approach ensures uniform dispersion of the functionalized CNTs throughout the PLA matrix, leading to enhanced electrical conductivity.

Keramati et al. [305] prepared PLA/GNPs nanocomposite film by means of solution casting method. Prepared film were characterized to check the influence of graphene nanoparticles dispersion on the mechanical properties of PLA. 3 wt.% of graphene nanoparticles was added for the fabrication of PLA nanocomposite. Tensile test results showed that the incorporation of GNPs in PLA result in the enhancement of mechanical properties, like elastic modulus of PLA/GNP was increased up to 11.36% as compared to neat PLA film. 4.76% increment was recorded in the tensile strength of PLA/GNPs nanocomposite with respect to neat PLA. 31.57% decrement was recorded in% elongation at breakin nanocomposite relative to neat PLA film. Due to increase in the elastic modulus the crystallinity of PLA got improved. Al Saleh et al. [306] investigated the surface area and size of GNPs impact on PLA composites. It was found that larger surface area and smaller GNPs improved electrical conductivity and electromagnetic interference attenuation by absorption, but at high GNP loading (30 wt%), these properties decreased due to increased contact resistance between GNPs. Ansari et al. [307] investigated the influence of carbon nanofibers (CNFs) into PLA matrix. The specimens were prepared via 3D printing. The results revealed that the impact strength is significantly influenced by infill density and print speed. The addition of carbon fiber notably enhanced hardness, with a maximum value of 79.6 (Shore D), marking a 37.95% improvement over pure PLA. This improvement is attributed to the presence of CF in



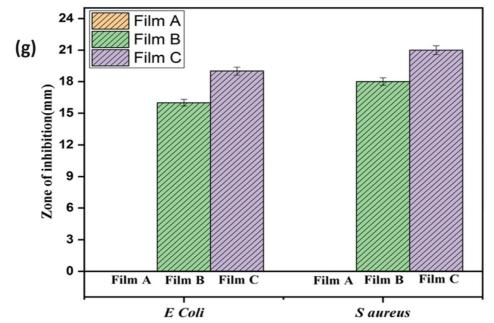


Fig. 5

Elemental analysis and antibacterial activity of PLA, PLA/ZnO and PLA/ZnO nano rods composites. Reprinted with changes and permission from [303].

the composite material. Babu et al. [308] prepared PLA/CNFs composites and investigated the effect of printing parameters on mechanical properties of composites. Garcia et al. [309] fabricated the PLA/GNPs composites by 3D printing and investigated the effect of geometric perameterson PLA-basedcomposites. Wei et al. [310] prepared the PLA/CNTs composites and investigated their mechanical and morphological properties. These interactions played a crucial role in adsorption processes, affecting the interfacial interaction, overall structure, and properties of the composite materials.

## 7.5 Multi-reinforcement system

Many hybrid composites of PLA containing polymers, natural fibers, metals, metal oxides, and carbon-based nanoparticles have

been studied for different applications. Ali et al. [311] prepared the PLA/Mg/BG composites by solution casting and hot compression. First, PLA/chloroform was poured on Mg wires, then chloroform was evaporated which left PLA/Mg lamina. Next, PLA/chloroform was sprayed on BG fibers and PLA/BG lamina was prepared. Finally, PLA/MG/BG composites with various volume fraction of Mg and BG were prepared by hot compression process. 25% enhancement in tensile strength was recorded with the addition of 30 vol.% of Mg wires and 10 vol.% of BG fibers. The novel composite material exhibited excellent mechanical and biocompatibility properties, making it a promising alternative to traditional metallic implants that are associated with long-term health risks. Bakina et al. [312] prepared the PLA/Fe<sub>3</sub>O<sub>4</sub> composites to increase the mechanical and biocompatibility

of composites as compared to pure PLA. Basheer et al. [313] developed the hybrid composite by reinforcing PLA with 1 wt% carbon fiber and 1 wt% graphene. Mechanical testing revealed that the 3D printed hybrid PLA material exhibited a significantly higher tensile strength of 63 MPa compared to 31 MPa for the non-3D printed material. This enhanced material holds promise for applications in the automotive and consumer product industries due to its improved mechanical properties.

Rashidi et al. [314] prepared PLA/ZnO, PLA/Ag<sub>3</sub>PO<sub>4</sub>, and PLA/Ag<sub>3</sub>PO<sub>4</sub> /ZnO nanocomposites by using the solution casting method. SEM analysis was conducted to check the surface morphology. The hydrolytic degradation method was employed to check weight loss behavior in prepared samples. The uniform distribution of nanoparticles at their low concentrations in PLA was observed in SEM images. Hydrolytic degradation results showed that ZnO nanoparticles accelerated the degradation property of nanocomposites, while Ag<sub>3</sub>PO<sub>4</sub> retarded the degradation property. The catalytic behavior of ZnO could be the main reason for the reduction in the hydrolytic constancy of PLA. Wang et al. [315] prepared the PLLA/Mg<sub>65</sub>Zn<sub>35</sub>Ca<sub>5</sub> composites by the hot Injection process. In the first step, PLLA/Mg<sub>65</sub>Zn<sub>35</sub>Ca<sub>5</sub> composites were prepared by solvent casting using dichloromethane solvent. Then As-casted composite pieces were cut into the mold and heated to 180 °C for 5 min and then injected into a copper mold. The corrosion properties of composites were improved while mechanical properties were decreased.

Canales et al. [316] conducted a study focused on the development of electrospun fibers for potential use in bone tissue engineering. They created PLA fibers containing 10 and 20 wt.% of BG and MgO nanoparticles, each with specific sizes (27 nm for n-BG and 23 nm for n-MgO). The incorporation of both n-BG and n-MgO nanoparticles into PLA was found to have a synergistic effect, enhancing the material's bioactivity and antimicrobial properties. While neat PLA and PLA/n-MgO scaffolds exhibited an average fiber diameter of approximately 1.7  $\mu$ m, PLA/n-BG and PLA/n-BG/n-MgO fibers showed a significant diameter increase to around 3.1  $\mu$ m. Chen et al. [317] fabricated the PLA/wheat straw composites to improve compatibility and mechanical properties. Dadashi et al. [318] investigated the effect of ZnO on the degradation PLA. Eichers et al. [319] incorporated biobased materials such as cellulose nanocrystals (CNC), distillers dried grains with solubles (DDGS), PEG, and maleic anhydride (MA) into PLA composites. Gama et al. [320] investigated the effect of cellulose fibers into PLA. Goni-Ciaurriz et al. [321] studied the effect of cellulose acetate (CA) on PLA. They prepared composite films of PLA and CA incorporating TiO<sub>2</sub> nanoparticles and  $\beta$ -cyclodextrin grafted TiO<sub>2</sub> particles. Photo and thermo-degradation studies were conducted, revealing that higher TiO<sub>2</sub> concentrations led to increased color variations, structural modifications, and weight loss in both CA and PLA films. The maximum weight loss observed was 9.3% for CA with 5% TiO2 and 5.1% for PLA with the same TiO2 content.  $\beta$ cyclodextrin-modified TiO2 NPs showed a lesser impact on photodegradation compared to unmodified TiO<sub>2</sub> NPs. To enhance antibacterial properties, benzoic acid (BA) and sorbic acid (SA) were incorporated into  $\beta$ -cyclodextrin-TiO<sub>2</sub> NPs. The composite

films, particularly CA with 5% TiO2 NPs, exhibited strong antibacterial activity, achieving a 71% inhibition of Escherichia coli and an 88% inhibition of Staphylococcus aureus. Jafari et al. [322] fabricated the 3D scaffolds using PLA, poly( $\varepsilon$ -caprolactone) and zirconia nanoparticles (n-ZrO<sub>2</sub>) through freeze-drying. Kananathan et al. [323] prepared the composites of PLA and coconut wood using 3D printing. Kuang et al. [324] used shishkebabs techniques to improve the properties of PLA. Arastouei et al. [325] fabricated the PLA/akermanite porous scaffolds for bone defects using FDM. These scaffolds were further coated with gentamicin-loaded gelatin microspheres. Morphological studies assessment through SEM revealed interconnected pores with diameters ranging from 200 to 400  $\mu$ m. Cell culture studies using the MG-63 cell line demonstrated that increasing amounts of akermanite led to enhanced cell proliferation, growth, and viability. Alizarin red assay indicated a significant increase in calcium deposition with higher levels of akermanite. The activity of alkaline phosphatase (ALP) showed a notable increase over time in scaffolds containing akermanite compared to pure PLA scaffolds, suggesting a positive influence on cellular activity. Evaluation of gentamicin release from gelatin microspheres, crosslinked for different durations and soaked in SBF, indicated an increasing release of the drug over time, although it decreased with longer cross-linking durations.

Li et al. [326] developed a novel approach to create fully bio-based PLA composites with enhanced flame retardancy, and accelerated degradation in soil. They synthesized a biodegradable additive, PA/CHTM, comprising phytic acids and chitosan microspheres. The incorporation of PA/CHTM into PLA improved its tensile properties, flame retardancy, and UVblocking capabilities. The tensile strength was well-maintained, and elastic modulus significantly increased. Moreover, PA/CHTM effectively delayed the photoaging of PLA by quenching free radicals, resulting in less than 10% UV light penetration and a substantially higher ultraviolet protection factor. Importantly, the presence of PA/CHTM accelerated the degradation of PLA, which is advantageous for biodegradable materials. Liao et al. [327] prepared the PLA/TiO<sub>2</sub>/wheat strawcomposites and studied the effect of TiO<sub>2</sub> on mechanical properties of PLA. Nguyen et al. [328] prepared the PLA-starch nanocomposites. Qiu et al. [329] enhanced the properties of PLA a bioplastic that is flammable, UV-sensitive, and slow to degrade naturally. To address these limitations, the researchers prepared a multifunctional bioderived additive called PA/TA-CS. This additive was created through a grafting reaction involving tannic acid (TA) and chitosan (CS), with a coating of phytic acid (PA) to improve PLA comprehensively. The findings showed that incorporating only 3% PA/TA-CS into PLA resulted in several significant improvements. It increased the Limiting Oxygen Index (LOI) value to 26.9%, elevated the UL-94 flammability rating to V-0, and blocked nearly 99% of UV light. This study represents a nature-inspired approach to enhance the performance and extend the service life of bioplastics. Shahar et al. [330] prepared the kenaf/PLA composite with varying filler concentrations (3%, 5%, and 7% by weight), and composite filaments were extruded and utilized in 3D printing to create test specimens. The study focused on evaluating crucial factors such as density,

Table 7
Summary of results on different type of composites of PLA.

Ref.	Matrix material	Reinforcement material	Fabrication method	Biocompatibility	Degradation results	Mechanical results
[284]	PLA pellets $M_W$ – 39,089 Density – 1.24 g/cm <sup>3</sup> $\eta$ – 1.226 $T_m$ – 160 °C Shenzhen Esun Industrial Co., Ltd	Mg particles Weight%– 5% (3.6 vol.%)	Solvent casting The composite was melted at 170 °C in vacuum furnace and recast into mold	Cell viability was reached to 102.4% after 4 days incubation.	pH value of PLA/Mg composite was 7.675, while the pH value of PLA was 7.54 after the 4 weeks immersion in PBS solution. 3.49% weight gain due to the apatite deposition. 47% retention in <b>M</b> <sub>w</sub>	$M_w$ was decreased to 35017with the addition of 5% Mg which show decreased crystallinity.
[285]	PLLA	Mg particles Size – 45 µm Acid-washed Mg powder was put in silane coupling agent for surface modifications Weight%– 1 to 5%	Injection molding	Exhibit improved cell viability (87%)	Showed increased weight loss with 0.22 mg/day	Exhibit improved tensile strength (58 MPa), and bending strength (100 MPa)
[311]	PLA pellets $M_{W}$ – 90,000 to 120,000 $T_{m}$ – 170.9 °C $T_{g}$ – 61.3 °C	Mg alloy (AZ31) wires and BG fibers Diameter – 313 μm and 20 to 40 μm Volume fraction – 30% and 10%	Solution casting& hot compression process	Not reported	10% retention in strength after the 7 days immersion in PBS	Tensile strength was improved from 60 to 108.7 MPaby adding 30% Mg and then increased to 135.9 MPa with the addition of 10% BG
[334]	PLA pellets $M_{W}$ = 90,000 to 120,000 $T_{m}$ = 188 to 210 °C $T_{a}$ = 55 to 60 °C	Mg alloy (AZ31) wires	Solvent casting Prepared laminae were stacked inside a cavity, preheated to melt temperature and pressure of 4 MPa is applied	Not reported	28% and 75% retention in tensile modulus and strength after the 56 days immersion.	3 times increase in tensile strength and significant increase in modulus.
[315]	PLLA	Mg <sub>65</sub> Zn <sub>30</sub> Ca <sub>5</sub> powder Weight%– 5%	Hot Injection Solvent Casting using dichloromethane solvent As-casted composite pieces were cut into the mold and heated to 180 °C for 5 min and then injected into copper mold.	Cell viability – 80% of control Milder cell growth environment	Showed high corrosion resistance	Decreased mechanical strength as compared to PLLA
[288]	PLA Number average <b>M</b> w– 78,000	Mg-2 Zn (98 wt.% of Mg and 2 wt.% of Zn) wires Diameter – 0.3 mm Wires were treated by microarc oxidation	Hot press+ Hot drawn 5 vol.% Three hot drawn passes	Not reported	Not reported	Bending strength – 207 MPa Mechanical properties were increased by increasing the content of Mg-2 Zn roads and number of passes.
[239]	PLGA (75:25)		Low temperature rapid prototyping 3D printing Wight ratio of PLGA/TCP/Mg was 16/2/1 and 16/2/2	Bone formation was prom	7% volume change exhibit fast degradation	Improvement in elastic modulus and compressive strength.
[295]	PLA <i>T<sub>m</sub></i> – 150 °C <i>T<sub>g</sub></i> – 61 °C	ZnO nanoflowers Weight% – 0.5	Solvent casting	% Reduction of bacterial colonies 99.33 after 24 h against bacteria Listeria monocytogenes and E. coli	For PLA 10% weight loss was at 323.1 °C While for PLA/ZnO same weight loss was at 253.7 °C	Tensile strength – 32.2 MPa Elastic modulus – 912.2 MPa Tensile strength was increased from 26.5 to 32.2 by addding0.5 wt.% ZnO.

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#### Table 7 (continued)

Ref.	Matrix material	Reinforcement material	Fabrication method	Biocompatibility	Degradation results	Mechanical results
[335]	PLA $M_{W}$ – 200 kDa $T_{g}$ – 54.3 °C $T_{m}$ – 167.3 °C Biomer Inc	Cubic ZnO nanoparticles Size – 50 to 100 nm Average diameter – 56.1 nm Weight% – 0.5 to 1.5	Solvent casting 53 µm film was prepared	Not reported	Composites showed stronger antimicrobial activity against E. coli and L. monocytogenes	Tensile strength – 58.4 MPa Elastic modulus – 2570 MPa Elongation – 4.5% Tensile strength was increased from 42.5 to 58.4 by addding0.5 wt.% ZnO.
[295]	PLA pellets $M_w$ – 74,000 Density – 1.24 g/cm <sup>3</sup> $T_m$ – 147 °C $T_q$ – 54 °C	ZnO powder Density – 5.606 g/cm <sup>3</sup> Diameter – 10 to 30 nm Length – 100 nm Weight% – 0.5 to 1.5	Solvent casting Resulting surfaces were stored inside a desiccator containing magnesium nitride solution	Not reported	Melting temperature was maintained	Tensile strength – 55.56 MPa Elastic modulus – 2460 MPa Elongation – 2.53%
[196]	2Chitosen/PLA	Extrusion + Annealing		Not reported	Not reported	Showed reduced tensile and compressive strength but annealing increased the mechanical properties.
[252]	10.7PLGA/HA		Direct grafting method	<del></del>	Not reported	Significant improvement in modulus, elongation at break and tensile strengths.
[200]	PLA/PBS (50/50)	CNF Diameter – 409 nm	Melt extrusion	MTT assay at 14 days showed 94.12% increase in cell proliferation as compared to Pure PLA	Did not significantly affect enzymatic hydrolysis as compared to PLA/PBS	Tensile strength – 3.46 MPa Elongation modulus – 119.6 MPa Elongation – 115.6%
[262]	PLA	HA (10 to 50 wt.%) Diameter – 50 nm	3D printing	CT scans were performed at 3 months after implantation in the rabbit femur. PLA/TCP samples exhibit improved cell activity.	The results showed significant improvement in bone tissue volume and mineral density. PLA/30TCP composites approx 50% improvement in degradation.	PLA/HA composites becomes brittle and approx. 35% decrease in compression strength (25 MPa) with the addition of 30% HA
[325]	PLA	Akarmanite (10, 20 & 30 wt.%)	3D printing	Cell viability results of MG-63 cells showed higher level of cell viability as compared to pure PLA. The scaffolds containing 20% and 30% akarmanite presented a cell viability of 97.72% and 96.88%.	Exhibit higher resistance to degradation	Lower permeability and highe porosity decreases strength.
[293]	PLA	316 L stainless steel (diameter – 20 μm) and Iron (diameter – 20 to 45 μm)	Fused filament fabrication	PLA/316 L exhibit 80% less cell viability, while PLA/Fe exhibit 14.1% increase in cells viability.	Immersion test in PBS solution showed, the 12.4% increase in weight loss.	Approx. 2 times increase in strength and compressive modulus as compared to pure PLA. Fatigue life increases for both composites.
[336]	PLA	HA (70:30) Particle size – 50 μm	3D bioplotter	Bigger efficiency for the treatment of larger bone defects	Not Reported	Not Reported
[262]	PLA	HA (70:30) Particle size – 50 μm	3D bioplotter	Enhances the ontogenesis in vivo	Not Reported	Does not significantly influence the mechanical properties
		·				(continued on next p

## Table 7 (continued)

Ref.	Matrix material	Reinforcement material	Fabrication method	Biocompatibility	Degradation results	Mechanical results
[337]	PLA	HA (70:30) Particle size – 50 to 80 nm	FDM	Bone growth is significantly higher than pure PLA	Enhanced degradation rate	Compressive strength – 25 MPa Decrease in compressive as compressive pure PLA
[338]	PLA	HA (50:50) Particle size – 75 nm	FDM	Vascular bundles allows the construction of large volume bone tissues in vivo trails	Not Reported	Compressive strength – 17.8 MPa Decrease in compressive as compressive pure PLA
[339]	PLA	HA (85:15) Particle size – 21 μm	MDS	Allow cellsgrowth around the composites	Not Reported	Not Reported
[340]	PLA	HA (90:10) Particle size – 50 μm	FFF	Improved bone forming ability	Not Reported	Not Reported
[341]	PLA	CaP coating 98:2	FDM	Promotes new bone formation	Not Reported	Elastic modulus – 0.510 GPa Compressive strength – 18.22 MPa Small decrease in mechanical properties
[342]	PLA	HA (80:20) Particle size – 50 μm	FDM	Presents the best bone integration	Not Reported	Elastic modulus – 10.12 MPa Compressive strength – 31.18 MPa Improvement in Mechanical properties
[343]	PLLA	eta–TCP	3D Bioplotter	Tests in MG-63 showed improved bone tissue growth due to the use of $\beta$ -TCP	71% remaining scaffold after the 12 weeks	
[344]	PLA	Apatite Wollastonite 50:50	3D printing	Promote growth of new bone and showed improved osseointegration.	Not reported	Match to bone properties
[345]	PLA	HA 85:15	MDS	Promotes cell proliferation and no inflammation reaction.	Good biodegradation activity	Not Reported
[346]	PLA	Ostacalcium phosphate 40:60	MEB co-precipitation method	Stimulated the osteogenic differentiation	Not Reported	Approx. similar properties to bone

impact strength, and fatigue resistance. Zhao et al. [331]improved the cross linking of PLA to decrease the brittleness of PLA. The UV-crosslinked PLA nanofibrils greatly enhanced foaming ability and outstanding thermal insulation properties with a low thermal conductivity. This innovative approach offers potential applications where lightweight, thermally insulating materials with improved mechanical strength are desired.

Liu et al. [332] conducted a study involving the preparation of PLA/PBAT composites modified by polyvinyl alcohol (PVA) and cellulose nanocrystals (CNC). They began by preparing CNC from bagasse pulp through sulfuric acid hydrolysis and characterized its properties. Next, they used a complex plasticizer to prepare thermoplastic polyvinyl alcohol (TPVA) and CNC-modified TPVA. These materials were blended with PBAT and PLA composite material (COM) using high melt extrusion and blown film techniques. The study focused on assessing the impact of CNC on the UV aging properties of the materials. The results showed that CNC improved the bonding, and anti-aging performance of the composites. Yiga et al. [333]. suggested that modified rice husks, especially those treated with alkali, are preferable as reinforcement materials in flame-retardant fiber-reinforced PLA composites compared to unmodified rice husks. These modifications enhance their thermal stability and flame-retardant properties, making them valuable for various applications. To improve the antimicrobial properties of PLA-based composites, metal nanoparticles like copper-zinc alloy particles and carbonbased nanoparticles have been used as additives [205]. These particles enhance the antimicrobial and mechanical properties with improved thermal stability.

The results on different PLA-based composites are summarized in Table 7. Various methods are employed for the fabrication of PLA-based composites, each with its own set of advantages, disadvantages, and limitations. These methods include solution casting, extrusion, injection molding, and 3D printing, each serving different purposes and applications [347-349]. Solution casting, entails the dissolution of PLA in a suitable solvent, such as chloroform, through overnight stirring [350]. To ensure complete dispersion of nanoparticles, they are incorporated into the solution and further homogenized through sonication. The mixed solution is then poured into a petri dish, where it undergoes a 24-hour drying process, culminating in the formation of a thin film composed of PLA nanocomposite. This technique is notable for its ability to precisely control nanoparticle dispersion within the PLA matrix, achieving a high degree of material uniformity. It adheres to Stokes' Law for solute and solvent mixing. However, solution casting is relatively time-consuming, involves the use of hazardous solvents like THF, and is best suited for thin film fabrication rather than complex shapes or bulk materials. Widely employed for bulk PLA composite production, molding is a technique that starts with the compression of PLA granules using a ram or screw. These granules are then heated to the point of melting and subsequently injected under pressure into a cold, split mold. The polymer solidifies within the mold and is subsequently ejected upon mold opening. This solution forms the foundation for the subsequent electrospinning process [351]. The electrospinning setup comprises essential components, including a syringe housing the composite solution, a metal

needle or nozzle connected to the syringe, a grounded collector (typically a rotating drum or stationary plate), a power supply and an adjustable platform to control the distance between the collector and needle tip. The electrospinning process is initiated by applying a high voltage to the needle or nozzle, generating an electric field that causes the composite solution at the needle's tip to form a distinctive Taylor cone shape—an indicator that the solution is ready for electrospinning [352,353]. Within this electric field, a jet of the composite solution is expelled from the Taylor cone toward the grounded collector. During this journey, rapid solvent evaporation occurs, leading to the solidification of PLA and other additives. This solidification transpires before the fibers reach the collector, resulting in the creation of ultrafine fibers with diameters spanning from nanometers to micrometers.

#### 8 Conclusion

Designing PLA-based biomedical devices requires a brief understanding of some important characteristics of PLA-based biomaterials such as biodegradability, biocompatibility and mechanical properties. Proper selection of synthesis route and the improvement in polymerization process with the use compatibilizer and catalysts expand the range of biomedical applications of PLA in various fields, including orthopedics and cardiology. Preparation of copolymers, blends or composites is a common practice for adjusting the degradation and mechanical properties of PLA for required applications. This review article summarizes the degradation behavior, biocompatibility and mechanical properties of PLA-based biomaterials and biomedical devices. The potential of PLA-based biomaterials in others applications is briefly discussed.

In vitro and in vivo results on different devices made of PLA-based biomaterials make them suitable as compared to conventional biomedical devices due to the their complete resorption or degradation in human body. Biomedical grade PLLA is most widely used biodegradable or bioabsorbable biopolymer for biomedical devices. Copolymers or blends of PLA-based biodegradable materials such as PLA/PGA, PLA/PHBV, PLA/PCL, PLA/starch showed improved properties for biomedical applications.

PLA composites showed excellent potential for variety of next-generation biomedical applications due to their unique combinations of mechanical strength, biodegradability and biocompatibility. Calcium-phosphate-based reinforcements such as HA and TCP are the most widely used materials for the preparation of PLA-based composites for innovative biomedical devices. PLA/β-TCP composites exhibit improved strength, biocompatibility and the more similar properties to the bone. The addition of various metal-based particles such as Mg, Ca, Zr, and Zn has been instrumental in significantly augmenting both the mechanical and degradation properties of PLA. Oxide nanoparticles such as ZnO, and Fe<sub>3</sub>O<sub>4</sub>, TiO<sub>2</sub> also exhibit the intriguing ability to initiate PLA polymerization and enhance their distribution within the polymer matrix. Composites of PLA containing carbon-based nanoparticles such as PLA/GNP exhibit improved antibacterial and mechanical properties. Many hybrid composites containing polymers, calcium phosphate-based materials, metals, natural fibers, and metal oxide reinforcements have been fabricated and exhibit improved properties. Overall, the fabrication of PLA-based composites is an important research area with a potential in the biomedical field.

Various factors, including polymerization reactions, rheological, mechanical, thermal, and barrier properties, impact the performance of PLA polymers. Additive manufacturing, particularly 3D printing, is emerging as a promising avenue for PLA nanocomposites. It allows for the efficient production of complex and customized structures, expanding their potential applications, especially in the biomedical field and the post-pandemic additive manufacturing industry. Further, research is required to address the challenges and limitations of PLA-based materials. The research and development for the preparation high-strength PLA-based materials is required to replace the conventional orthopedic materials like titanium.

## **Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### **Data availability**

No data was used for the research described in the article.

### **CRediT authorship contribution statement**

**Muzamil Hussain:** Writing – original draft, Investigation. **Shahzad Maqsood Khan:** Methodology, Conceptualization. **Muhammad Shafiq:** Resources, Formal analysis. **Naseem Abbas:** Writing – review & editing, Resources, Data curation, Conceptualization.

#### References

- [1] Z.U. Arif, M.Y. Khalid, R. Noroozi, M. Hossain, H.T.H. Shi, A. Tariq, S. Ramakrishna, R. Umer, Additive manufacturing of sustainable biomaterials for biomedical applications, Asian J. Pharm. Sci. 18 (2023) 100812, doi:10.1016/ J.AJPS.2023.100812.
- [2] E.J. Dil, A. Ajji, A. Saffar, Polyester materials in biomedical applications, Polyest. Film. (2023) 306–342, doi:10.1002/9781119535775.CH8.
- [3] G.K. Jena, R. Parhi, Applications of composite materials in drug delivery systems, green sustain, Process Chem. Environ. Eng. Sci. Biomed. Appl. Green Compos. (2023) 111–130, doi:10.1016/B978-0-323-95169-2.00004-3.
- [4] R.N. Darie-Niţă, M. Râpă, S. Frackowiak, Special features of polyester-based materials for medical applications, Polym 14 (2022) 951 Page14 (2022) 951, doi:10.3390/POLYM14050951.
- [5] V. Allizond, S. Comini, A.M. Cuffini, G. Banche, Current knowledge on biomaterials for orthopedic applications modified to reduce bacterial adhesive ability, Antibiot 11 (2022) 529 Vol.Page11 (2022) 529, doi:10.3390/ ANTIBIOTICS11040529.
- [6] N.A.A.B. Taib, M.R. Rahman, D. Huda, K.K. Kuok, S. Hamdan, M.K. Bin Bakri, M.R.M. Bin Julaihi, A. Khan, A review on poly lactic acid (PLA) as a biodegradable polymer, Polym. Bull. 80 (2023) 1179–1213, doi:10.1007/S00289-022-04160-Y/ TABLES/14.
- [7] T.A. Swetha, A. Bora, K. Mohanrasu, P. Balaji, R. Raja, K. Ponnuchamy, G. Muthusamy, A. Arun, A comprehensive review on polylactic acid (PLA) synthesis, processing and application in food packaging, Int. J. Biol. Macromol. 234 (2023) 123715, doi:10.1016/j.IJBIOMAC.2023.123715.
- [8] S. S, A.P. RG, G. Bajaj, A.E. John, S. Chandran, V.V. Kumar, S. Ramakrishna, A review on the recent applications of synthetic biopolymers in 3D printing for biomedical applications, J. Mater. Sci. Mater. Med (2023) 3412 34 (2023) 1–22, doi:10.1007/S10856-023-06765-9.
- [9] M.U.A. Khan, M.A. Aslam, M.F. Bin Abdullah, A. Hasan, S.A. Shah, G.M. Stojanović, Recent perspective of polymeric biomaterial in tissue engineering—a review, Mater. Today Chem. 34 (2023) 101818, doi:10.1016/J. MTCHEM.2023.101818.
- [10] H. Katepogu, Y.J. Wee, K. Anu Appaiah, S.V. Chinni, S.C.B. Gopinath, A. Syed, M. Verma, V.R. Lebaka, Lactic acid production by Pediococcus pentosaceus

- HLV1 from banana crop residue: an economic and renewable resource, Biomass Convers. Biorefinery (2023) 1–11, doi:10.1007/S13399-023-04481-6/FIGURES/  $^{8}$
- [11] S.S. Ali, E.A. Abdelkarim, T. Elsamahy, R. Al-Tohamy, F. Li, M. Kornaros, A. Zuorro, D. Zhu, J. Sun, Bioplastic production in terms of life cycle assessment: a state-of-the-art review, Environ. Sci. Ecotechnol 15 (2023) 100254, doi:10. 1016/J.ESE.2023.100254.
- [12] Y. Zhang, Z. Xu, M. Lu, X. Ma, S. Chen, Y. Wang, W. Shen, P. Li, M. Jin, High titer (>200g/L) lactic acid production from undetoxified pretreated corn stover, Bioresour. Technol. 388 (2023) 129729, doi:10.1016/J.BIORTECH.2023.129729.
- [13] A. Khan, S.M. Sapuan, J. Yusuf, V.U. Siddiqui, E.S. Zainudin, M.Y.M. Zuhri, B.T.H. Tuah Baharuddin, M.A. Ansari, A.A.A. Rahman, An examination of cutting-edge developments in Bamboo-PLA composite research: a comprehensive review, Renew. Sustain. Energy Rev. 188 (2023) 113832, doi:10.1016/J.RSER.2023.113832.
- [14] S. Chopra, K. Pande, P. Puranam, A.D. Deshmukh, A. Bhone, R. Kale, A. Galande, B. Mehtre, J. Tagad, S. Tidake, Explication of mechanism governing atmospheric degradation of 3D-printed poly(lactic acid) (PLA) with different in-fill pattern and varying in-fill density, RSC Adv 13 (2023) 7135–7152, doi:10.1039/D2RA07061H.
- [15] W.J. Chong, S. Shen, Y. Li, A. Trinchi, D. Pejak Simunec, I. (Louis) Kyratzis, A. Sola, C. Wen, Biodegradable PLA-ZnO nanocomposite biomaterials with antibacterial properties, tissue engineering viability, and enhanced biocompatibility, Smart Mater. Manuf. 1 (2023) 100004, doi:10.1016/J.SMMF. 2022.100004.
- [16] M. Zarei, S.S. Sayedain, A. Askarinya, M. Sabbaghi, R. Alizadeh, Improving physio-mechanical and biological properties of 3D-printed PLA scaffolds via in-situ argon cold plasma treatment, Sci. Reports (2023) 131 13 (2023) 1–16, doi:10.1038/s41598-023-41226-x.
- [17] R. Murugapandian, S. Clement, V. Uthirapathy, Fabrication and in vitro drug delivery evaluation of cephalexin monohydrate-loaded PLA:PVA/HAP:tiO2 fibrous scaffolds for bone regeneration, ACS Omega 8 (2023) 5017– 5032, doi:10.1021/ACSOMEGA.2C07701/ASSET/IMAGES/LARGE/AO2C07701\_ 0012.JPEG.
- [18] M. Mohammadi-Zerankeshi, R. Alizadeh, 3D-printed PLA-Gr-Mg composite scaffolds for bone tissue engineering applications, J. Mater. Res. Technol. 22 (2023) 2440–2446, doi:10.1016/J.JMRT.2022.12.108.
- [19] N.İ. Büyük, D. Aksu, G. Torun Köse, A. Gamze, T. Köse, N.\_. Irem, B. Uy\(\xi\) Uk, D. Aksu, G. Torun, K. Ose, Effect of different pore sizes of 3D printed PLA-based scaffold in bone tissue engineering, Int. J. Polym. Mater. Polym. Biomater. 72 (2023) 1021–1031, doi:10.1080/00914037.2022.2075869.
- [20] S.N. Kalva, F. Ali, C.A. Velasquez, M. Koç, 3D-Printable PLA/Mg composite filaments for potential bone tissue engineering applications, Polym 15 (2023) 2572 Page15 (2023) 2572, doi:10.3390/POLYM15112572.
- [21] A. Mattesini, S. Bartolini, C.S. Dini, S. Valente, G. Parodi, M. Stolcova, F. Meucci, C. di Mario, The DESolve novolimus bioresorbable Scaffold: from bench to bedside, J. Thorac. Dis. 9 (2017) S950, doi:10.21037/JTD.2017.07.25.
- [22] E. Tenekecioglu, R. Torii, Y. Katagiri, P. Chichareon, T. Asano, Y. Miyazaki, K. Takahashi, R. Modolo, R. Al-Lamee, K. Al-Lamee, C. Colet, J.H.C. Reiber, K. Pekkan, R. van Geuns, C.V. Bourantas, Y. Onuma, P.W. Serruys, Postimplantation shear stress assessment: an emerging tool for differentiation of bioresorbable scaffolds, Int. J. Cardiovasc. Imaging 35 (2019) 409–418, doi:10.1007/S10554-018-1481-3/FIGURES/5.
- [23] X. Li, Y. Lin, M. Liu, L. Meng, C. Li, A review of research and application of polylactic acid composites, J. Appl. Polym. Sci. 140 (2023) e53477, doi:10.1002/ APP.53477.
- [24] A. Mehmood, N. Raina, V. Phakeenuya, B. Wonganu, K. Cheenkachorn, The current status and market trend of polylactic acid as biopolymer: awareness and needs for sustainable development, Mater. Today Proc. 72 (2023) 3049–3055, doi:10.1016/J.MATPR.2022.08.387.
- [25] N. More, M. Avhad, S. Utekar, A. More, Polylactic acid (PLA) membrane—significance, synthesis, and applications: a review, Polym. Bull. (2022) 802 80 (2022) 1117–1153, doi:10.1007/S00289-022-04135-Z.
- [26] T.M. Joseph, A. Kallingal, A.M. Suresh, D.K. Mahapatra, M.S. Hasanin, J. Haponiuk, S. Thomas, 3D printing of polylactic acid: recent advances and opportunities, Int. J. Adv. Manuf. Technol. (2023) 1253 125 (2023) 1015–1035, doi:10.1007/S00170-022-10795-Y.
- [27] I. Alonso-Fernández, H.J. Haugen, M. López-Peña, A. González-Cantalapiedra, F. Muñoz, Use of 3D-printed polylactic acid/bioceramic composite scaffolds for bone tissue engineering in preclinical in vivo studies: a systematic review, Acta Biomater 168 (2023) 1–21, doi:10.1016/J.ACTBIO.2023.07.013.
- [28] T.A. Swetha, V. Ananthi, A. Bora, N. Sengottuvelan, K. Ponnuchamy, G. Muthusamy, A. Arun, A review on biodegradable polylactic acid (PLA) production from fermentative food waste - its applications and degradation, Int. J. Biol. Macromol. 234 (2023) 123703, doi:10.1016/J.IJBIOMAC.2023.123703.
- [29] H. Ramezani Dana, F. Ebrahimi, Synthesis, properties, and applications of polylactic acid-based polymers, Polym. Eng. Sci. 63 (2023) 22–43, doi:10.1002/ PEN.26193.
- [30] K. Kour, R. Kumar, G. Singh, G. Singh, S. Singh, K. Sandhu, Additive manufacturing of polylactic acid-based nanofibers composites for innovative

- scaffolding applications, Int. J. Interact. Des. Manuf. 2023 (2023) 1–25, doi:10.1007/S12008-023-01435-0.
- [31] F.A. Castillo Martinez, E.M. Balciunas, J.M. Salgado, J.M. Domínguez González, A. Converti, R.P. de, S. Oliveira, Lactic acid properties, applications and production: a review, Trends Food Sci. Technol. 30 (2013) 70–83, doi:10.1016/J. TIFS.2012.11.007.
- [32] V. Juturu, J.C. Wu, Microbial production of lactic acid: the latest development, Crit. Rev. Biotechnol. 36 (2016) 967–977, doi:10.3109/07388551.2015.1066305.
- [33] S. Jantasee, M. Kienberger, N. Mungma, M. Siebenhofer, Potential and assessment of lactic acid production and isolation – a review, J. Chem. Technol. Biotechnol. 92 (2017) 2885–2893, doi:10.1002/JCTB.5237.
- [34] A. Kumar, A. Thakur, P.S. Panesar, Lactic acid and its separation and purification techniques: a review, Rev. Environ. Sci. Biotechnol. 18 (2019) 823–853, doi:10. 1007/S11157-019-09517-W/TABLES/4.
- [35] Y. Wang, W. Deng, B. Wang, Q. Zhang, X. Wan, Z. Tang, Y. Wang, C. Zhu, Z. Cao, G. Wang, H. Wan, Chemical synthesis of lactic acid from cellulose catalysed by lead(II) ions in water, Nat. Commun. (2013) 41 4 (2013) 1–7, doi:10.1038/ncomms3141.
- [36] J. Park, H. Cho, D. Hwang, S. Kim, I. Moon, M. Kim, Design of a novel process for continuous lactide synthesis from lactic acid, Ind. Eng. Chem. Res. 57 (2018) 11955–11962, doi:10.1021/ACS.IECR.8B02419/SUPPL\_FILE/IE8B02419\_SI\_001.
- [37] A. Ahmad, I. Othman, K. Rambabu, G. Bharath, H. Taher, S.W. Hasan, F. Banat, Polymerization of lactic acid produced from food waste by metal oxide-assisted dark fermentation, Environ. Technol. Innov. 24 (2021) 101862, doi:10.1016/J. ETI.2021.101862.
- [38] T.L. de Albuquerque, J.E. Marques Júnior, L.P. de Queiroz, A.D.S. Ricardo, M.V.P. Rocha, Polylactic acid production from biotechnological routes: a review, Int. J. Biol. Macromol. 186 (2021) 933–951, doi:10.1016/J.IJBIOMAC.2021.07. 074
- [39] H. Desai, T. Mehta, N. Shah, Azeotropic dehydrative (solution) polycondensation of lactic acid to polylactic acid (PLA): a in-depth review of an overlooked method for manufacturing PLA, Polym. Technol. Mater. 62 (2023) 1394–1402, doi:10.1080/25740881.2023.2209644.
- [40] J. Yu, S. Xu, B. Liu, H. Wang, F. Qiao, X. Ren, Q. Wei, PLA bioplastic production: from monomer to the polymer, Eur. Polym. J. 193 (2023) 112076, doi:10.1016/ J.EURPOLYMJ.2023.112076.
- [41] A. Ahmad, F. Banat, H. Alsafar, S.W. Hasan, An overview of biodegradable poly (lactic acid) production from fermentative lactic acid for biomedical and bioplastic applications, Biomass Convers. Biorefin (2022) 1 (2022) 1–20, doi:10. 1007/\$13399-022-02581-3.
- [42] A. Zanoni, F. Tollini, C. Casiraghi, G. Storti, M. Sponchioni, D. Moscatelli, Functionalized lactic acid macromonomers via polycondensation as an alternative to ring opening polymerization, Can. J. Chem. Eng. 101 (2023) 4845– 4859, doi:10.1002/CJCE.24800.
- [43] M.S. Singhvi, S.S. Zinjarde, D.V. Gokhale, Polylactic acid: synthesis and biomedical applications, J. Appl. Microbiol. 127 (2019) 1612–1626, doi:10.1111/ IAM.14290.
- [44] R.M. Michell, V. Ladelta, E. Da Silva, A.J. Müller, N. Hadjichristidis, Poly(lactic acid) stereocomplexes based molecular architectures: synthesis and crystallization, Prog. Polym. Sci. 146 (2023) 101742, doi:10.1016/J. PROGPOLYMSCI.2023.101742.
- [45] J.E. Chellali, A.K. Alverson, J.R. Robinson, Zinc Aryl/Alkyl  $\beta$ -diketiminates: balancing accessibility and stability for high-activity ring-opening polymerization of rac-lactide, ACS Catal 12 (2022) 5585–5594, doi:10.1021/ ACSCATAL.2C00858/SUPPL\_FILE/CS2C00858\_SI\_008.CIF.
- [46] M.C. D'Alterio, I. D'Auria, L. Gaeta, C. Tedesco, S. Brenna, C. Pellecchia, Are well performing catalysts for the ring opening polymerization of 1-lactide under mild laboratory conditions suitable for the industrial process? The case of new highly active Zn(II) Catalysts, Macromolecules 55 (2022) 5115–5122, doi:10.1021/ACS. MACROMOL.2C00719/SUPPL\_FILE/MA2C00719\_SI\_004.CIF.
- [47] L. Cui, X. Wang, G. Szarka, N. Hegyesi, Y. Wang, X. Sui, B. Pukánszky, Quantitative analysis of factors determining the enzymatic degradation of poly(lactic acid), Int. J. Biol. Macromol. 209 (2022) 1703–1709, doi:10.1016/ J.IJBIOMAC.2022.04.121.
- [48] A.N. Mistry, B. Kachenchart, A. Wongthanaroj, A. Somwangthanaroj, E. Luepromchai, Rapid biodegradation of high molecular weight semicrystalline polylactic acid at ambient temperature via enzymatic and alkaline hydrolysis by a defined bacterial consortium, Polym. Degrad. Stab. 202 (2022) 110051, doi:10.1016/J.POLYMDEGRADSTAB.2022.110051.
- [49] W. Ali, H. Ali, S. Gillani, P. Zinck, S. Souissi, Polylactic acid synthesis, biodegradability, conversion to microplastics and toxicity: a review, Environ. Chem. Lett. (2023) 213 21 (2023) 1761–1786, doi:10.1007/ S10311-023-01564-8.
- [50] M.A. Elsawy, K.H. Kim, J.W. Park, A. Deep, Hydrolytic degradation of polylactic acid (PLA) and its composites, Renew. Sustain. Energy Rev. 79 (2017) 1346–1352, doi:10.1016/J.RSER.2017.05.143.
- [51] M. Zaborowska, K. Bernat, B. Pszczółkowski, A. Cydzik-Kwiatkowska, D. Kulikowska, I. Wojnowska-Baryła, Multi-faceted analysis of thermophilic

- anaerobic biodegradation of poly(lactic acid)-based material, Waste Manag 155 (2023) 40–52, doi:10.1016/J.WASMAN.2022.10.031.
- [52] J. He, T. Yu, Y. Li, Biodegradable thermoset poly(lactic acid) resin containing phosphorus: flame retardancy, mechanical properties and its soil degradation behavior, Int. J. Biol. Macromol. 235 (2023) 123737, doi:10.1016/J.IJBIOMAC. 2023.123737.
- [53] K. Janczak, G.B. Dąbrowska, A. Raszkowska-Kaczor, D. Kaczor, K. Hrynkiewicz, A. Richert, Biodegradation of the plastics PLA and PET in cultivated soil with the participation of microorganisms and plants, Int. Biodeterior. Biodegradation 155 (2020) 105087, doi:10.1016/J.IBIOD.2020.105087.
- [54] P. Srimalanon, B. Prapagdee, N. Sombatsompop, Soil inoculation with pseudomonas geniculata WS3 for accelerating the biodegradation process of in situ compatibilized PBS/PLA blends doped with HPQM, J. Polym. Environ. 28 (2020) 1138–1149, doi:10.1007/S10924-020-01670-6/TABLES/5.
- [55] Y. Boonluksiri, B. Prapagdee, N. Sombatsompop, Promotion of polylactic acid biodegradation by a combined addition of PLA-degrading bacterium and nitrogen source under submerged and soil burial conditions, Polym. Degrad. Stab. 188 (2021) 109562, doi:10.1016/J.POLYMDEGRADSTAB.2021.109562.
- [56] T. Rheinberger, J. Wolfs, A. Paneth, H. Gojzewski, P. Paneth, F.R. Wurm, RNA-inspired and accelerated degradation of polylactide in seawater, J. Am. Chem. Soc. 143 (2021) 16673–16681, doi:10.1021/JACS.1C07508/ASSET/IMAGES/LARGE/JA1C07508\_0008.JPEG.
- [57] G.X. Wang, D. Huang, J.H. Ji, C. Völker, F.R. Wurm, Seawater-degradable polymers—fighting the marine plastic pollution, Adv. Sci. 8 (2021) 2001121, doi:10.1002/ADVS.202001121.
- [58] A.A. Cuadri, J.E. Martín-Alfonso, Thermal, thermo-oxidative and thermomechanical degradation of PLA: a comparative study based on rheological, chemical and thermal properties, Polym. Degrad. Stab. 150 (2018) 37–45, doi:10.1016/J.POLYMDEGRADSTAB.2018.02.011.
- [59] M. Kervran, C. Vagner, M. Cochez, M. Ponçot, M.R. Saeb, H. Vahabi, Thermal degradation of polylactic acid (PLA)/polyhydroxybutyrate (PHB) blends: a systematic review, Polym. Degrad. Stab. 201 (2022) 109995, doi:10.1016/J. POLYMDEGRADSTAB.2022.109995.
- [60] R. Gunti, A.V. Ratna Prasad, A.V.S.S.K.S. Gupta, Mechanical and degradation properties of natural fiber-reinforced PLA composites: jute, sisal, and elephant grass, Polym. Compos. 39 (2018) 1125–1136, doi:10.1002/PC.24041.
- [61] K. Pelegrini, I. Donazzolo, V. Brambilla, A.M. Coulon Grisa, D. Piazza, A.J. Zattera, R.N. Brandalise, Degradation of PLA and PLA in composites with triacetin and buriti fiber after 600 days in a simulated marine environment, J. Appl. Polym. Sci. 133 (2016), doi:10.1002/APP.43290.
- [62] Q. Qin, Y. Yang, C. Yang, L. Zhang, H. Yin, F. Yu, J. Ma, Degradation and adsorption behavior of biodegradable plastic PLA under conventional weathering conditions, Sci. Total Environ. 842 (2022) 156775, doi:10.1016/J. SCITOTENV.2022.156775.
- [63] N.A. Rosli, M. Karamanlioglu, H. Kargarzadeh, I. Ahmad, Comprehensive exploration of natural degradation of poly(lactic acid) blends in various degradation media: a review, Int. J. Biol. Macromol. 187 (2021) 732–741, doi:10. 1016/J. URIOMAC 2021 07 196
- [64] V. Mazzanti, M. Salzano de Luna, R. Pariante, F. Mollica, G. Filippone, Natural fiber-induced degradation in PLA-hemp biocomposites in the molten state, Compos. Part A Appl. Sci. Manuf. 137 (2020) 105990, doi:10.1016/J. COMPOSITESA.2020.105990.
- [65] X. Lin, Saijilafu, X.Wu, K. Wu, J. Chen, L. Tan, F. Witte, H. Yang, D. Mantovani, H. Zhou, C. Liang, Q. Yang, K. Yang, L. Yang, Biodegradable Mg-based alloys: biological implications and restorative opportunities, (2022). https://doi.org/10. 1080/09506608.2022.2079367.
- [66] C. Li, C. Guo, V. Fitzpatrick, A. Ibrahim, M.J. Zwierstra, P. Hanna, A. Lechtig, A. Nazarian, S.J. Lin, D.L. Kaplan, Design of biodegradable, implantable devices towards clinical translation, Nat. Rev. Mater. 5 (2020) 61–81, doi:10.1038/ s41578-019-0150-z.
- [67] J.-W.W. Li, C.-F.F. Du, C.-X.X. Yuchi, C.-Q.Q. Zhang, Application of biodegradable materials in orthopedics, J. Med. Biol. Eng. 39 (2019) 633–645, doi:10.1007/S40846-019-00469-8/TABLES/12.
- [68] J. Russias, E. Saiz, R.K. Nalla, K. Gryn, R.O. Ritchie, A.P. Tomsia, Fabrication and mechanical properties of PLA/HA composites: a study of in vitro degradation, Mater. Sci. Eng. C 26 (2006) 1289–1295, doi:10.1016/J.MSEC.2005. 08.004
- [69] S. Gogolewski, M. Jovanovic, S.M. Perren, J.G. Dillon, M.K. Hughes, Tissue response and in vivo degradation of selected polyhydroxyacids: polylactides (PLA), poly(3-hydroxybutyrate) (PHB), and poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHB/VA), J. Biomed. Mater. Res. 27 (1993) 1135–1148, doi:10.1002/JBM.820270904.
- [70] S. Farah, D.G. Anderson, R. Langer, Physical and mechanical properties of PLA, and their functions in widespread applications — a comprehensive review, Adv. Drug Deliv. Rev. 107 (2016) 367–392, doi:10.1016/J.ADDR.2016.06.012.
- [71] R. Suuronen, T. Pohjonen, J. Hietanen, C. Lindqvist, A 5-year in vitro and in vivo study of the biodegradation of polylactide plates, J. Oral Maxillofac. Surg. 56 (1998) 604–614, doi:10.1016/S0278-2391(98)90461-X.
- [72] S.F. Hosseini, Z. Javidi, M. Rezaei, Efficient gas barrier properties of multi-layer

- films based on poly(lactic acid) and fish gelatin, Int. J. Biol. Macromol. 92 (2016) 1205–1214, doi:10.1016/J.IJBIOMAC.2016.08.034.
- [73] T. Messin, N. Follain, A. Guinault, C. Sollogoub, V. Gaucher, N. Delpouve, S. Marais, Structure and barrier properties of multinanolayered biodegradable PLA/PBSA films: confinement effect via forced assembly coextrusion, ACS Appl. Mater. Interfaces 9 (2017) 29101–29112, doi:10.1021/ACSAMI.7B08404/SUPPL\_ FILE/AM7B08404 SI 001.PDF.
- [74] A.K. Pal, V. Katiyar, Nanoamphiphilic chitosan dispersed poly(lactic acid) bionanocomposite films with improved thermal, mechanical, and gas barrier properties, Biomacromolecules 17 (2016) 2603–2618, doi:10.1021/ACS. BIOMAC.6800619/ASSET/IMAGES/MEDIUM/BM-2016-00619X\_0014.GIF.
- [75] M. Akrami, I. Ghasemi, H. Azizi, M. Karrabi, M. Seyedabadi, A new approach in compatibilization of the poly(lactic acid)/thermoplastic starch (PLA/TPS) blends, Carbohydr. Polym. 144 (2016) 254–262, doi:10.1016/J.CARBPOL.2016. 02.035
- [76] J.M. Ferri, D. Garcia-Garcia, L. Sánchez-Nacher, O. Fenollar, R. Balart, The effect of maleinized linseed oil (MLO) on mechanical performance of poly(lactic acid)thermoplastic starch (PLA-TPS) blends, Carbohydr. Polym. 147 (2016) 60–68, doi:10.1016/J.CARBPOL.2016.03.082.
- [77] M. Shahin, K. Munir, C. Wen, Y. Li, Magnesium matrix nanocomposites for orthopedic applications: a review from mechanical, corrosion, and biological perspectives, Acta Biomater 96 (2019) 1–19, doi:10.1016/j.actbio.2019.06.007.
- [78] G. Chandra, A. Pandey, Biodegradable Bone Implants In Orthopedic Applications: A Review, Elsevier Sp. z o.o., 2020, doi:10.1016/j.bbe.2020.02.003.
- [79] Y.P. Wang, Y.H. He, Z.J. Zhu, Y. Jiang, J. Zhang, J.L. Niu, L. Mao, G.Y. Yuan, In vitro degradation and biocompatibility of Mg-Nd-Zn-Zr alloy, Chinese Sci. Bull. 57 (2012) 2163–2170, doi:10.1007/s11434-012-5066-6.
- [80] T. Sathies, P. Senthil, C. Prakash, Application of 3D printed PLA-carbon black conductive polymer composite in solvent sensing, Mater. Res. Express 6 (2019) 115349, doi:10.1088/2053-1591/AB5040.
- [81] N.E. Duygulu, F. Ciftci, C.B. Ustundag, Electrospun drug blended poly(lactic acid) (PLA) nanofibers and their antimicrobial activities, J. Polym. Res. 27 (2020) 1–11, doi:10.1007/S10965-020-02215-0/FIGURES/8.
- [82] N. Régibeau, J. Hurlet, R.G. Tilkin, F. Lombart, B. Heinrichs, C. Grandfils, Synthesis of medical grade PLLA, PDLLA, and PLGA by a reactive extrusion polymerization, Mater. Today Commun. 24 (2020) 101208, doi:10.1016/J. MTCOMM.2020.101208.
- [83] A. Kumar, A.R. Weig, S. Agarwal, Balancing degradability and physical properties of amorphous poly(d,l-lactide) by making blends, Macromol. Mater. Eng. 307 (2022) 2100602, doi:10.1002/MAME.202100602.
- [84] L. Feng, X. Bian, G. Li, X. Chen, Compatibility and thermal and structural properties of poly(l -lactide)/poly(l - Co- d -lactide) Blends, Macromolecules 55 (2022) 1709–1718, doi:10.1021/ACS.MACROMOL.1C02599/SUPPL\_FILE/ MA1C02599 SI 001.PDF.
- [85] Z. Yan, X. Liao, G. He, S. Li, F. Guo, F. Zou, G. Li, Green and high-expansion PLLA/PDLA foams with excellent thermal insulation and enhanced compressive properties, Ind. Eng. Chem. Res. 59 (2020) 19244–19251, doi:10.1021/ACS.IECR. 0C02492/ASSET/IMAGES/MEDIUM/IE0C02492\_0014.GIF.
- [86] H.Y. Sintim, A.I. Bary, D.G. Hayes, L.C. Wadsworth, M.B. Anunciado, M.E. English, S. Bandopadhyay, S.M. Schaeffer, J.M. DeBruyn, C.A. Miles, J.P. Reganold, M. Flury, In situ degradation of biodegradable plastic mulch films in compost and agricultural soils, Sci. Total Environ. 727 (2020) 138668, doi:10.1016/I.SCITOTENV.2020.138668.
- [87] A. Chamas, H. Moon, J. Zheng, Y. Qiu, T. Tabassum, J.H. Jang, M. Abu-Omar, S.L. Scott, S. Suh, Degradation rates of plastics in the environment, ACS Sustain. Chem. Eng. 8 (2020) 3494–3511, doi:10.1021/ACSSUSCHEMENG. 9B06635/ASSET/IMAGES/LARGE/SC9B06635 0009.IPEG.
- [88] V. Gigante, I. Canesi, P. Cinelli, M.B. Coltelli, A. Lazzeri, Rubber toughening of polylactic acid (PLA) with poly(butylene adipate-co-terephthalate) (PBAT): mechanical properties, fracture mechanics and analysis of ductile-to-brittle behavior while varying temperature and test speed, Eur. Polym. J. 115 (2019) 125–137, doi:10.1016/J.EURPOLYMJ.2019.03.015.
- [89] M. Razavi, S.Q. Wang, Why is crystalline poly(lactic acid) brittle at room temperature? Macromolecules 52 (2019) 5429–5441, doi:10.1021/ACS. MACROMOL.9B00595/SUPPL\_FILE/MA9B00595\_SI\_005.MP4.
- [90] S.H. Lee, S.Y. Yeo, Improvement of hydrophilicity of polylactic acid (PLA) fabrics by means of a proteolytic enzyme from Bacillus licheniformis, Fibers Polym 17 (2016) 1154–1161, doi:10.1007/S12221-016-5923-Z/METRICS.
- [91] R. Hosseyni, M. Pooresmaeil, H. Namazi, Star-shaped polylactic acid-based triazine dendrimers: the catalyst type and time factors influence on polylactic acid molecular weight, Iran, Polym. J. (English Ed. 29 (2020) 423–432, doi:10. 1007/S13726-020-00807-7/FIGURES/4.
- [92] Y. Xu, L. Lin, S. Zeng, J. Liu, M. Xiao, S. Wang, Y. Meng, L. Sun, Synthesis of polylactide nanocomposites using an α-zirconium phosphate nanosheet-supported zinc catalyst via in situ polymerization, ACS Appl. Polym. Mater. 1 (2019) 1382–1389, doi:10.1021/ACSAPM.9B00155/SUPPL\_FILE/AP9B00155\_SI\_
- [93] V. Sessini, M. Palenzuela, J. Damián, M.E.G. Mosquera, Bio-based polyether from

- limonene oxide catalytic ROP as green polymeric plasticizer for PLA, Polymer (Guildf) 210 (2020) 123003, doi:10.1016/J.POLYMER.2020.123003.
- [94] G. Tutoni, M.L. Becker, Underexplored stereocomplex polymeric scaffolds with improved thermal and mechanical properties, Macromolecules 53 (2020) 10303–10314, doi:10.1021/ACS.MACROMOL.0C01468/ASSET/IMAGES/ MEDIUM/MA0C01468 0010.GIF.
- [95] J.C. Worch, H. Prydderch, S. Jimaja, P. Bexis, M.L. Becker, A.P. Dove, Stereochemical enhancement of polymer properties, Nat. Rev. Chem. 39 (3) (2019) 514–535 (2019), doi:10.1038/s41570-019-0117-z.
- [96] D. Kim, A. Bahi, L.Y. Liu, T. Bement, S. Rogak, S. Renneckar, F. Ko, P. Mehrkhodavandi, Poly(Lactide)-modified lignin nanofibers: investigating the role of polymer tacticity on fiber properties and filtration efficiency, ACS Sustain. Chem. Eng. 10 (2022) 2772–2783, doi:10.1021/ACSSUSCHEMENG.1C08053/ SUPPL\_FILE/SC1C08053\_S1\_001.PDF.
- [97] A. Milovanović, A. Sedmak, A. Grbović, Z. Golubović, M. Milošević, Influence of second-phase particles on fracture behavior of PLA and advanced PLA-X material, Procedia Struct. Integr. 31 (2021) 122–126, doi:10.1016/J.PROSTR. 2021.03.020.
- [98] L.G. Santos, L.C. Costa, L.A. Pessan, Development of biodegradable PLA/PBT nanoblends, J. Appl. Polym. Sci. 135 (2018) 45951, doi:10.1002/APP.45951.
- [99] J.I. Gug, J. Soule, B. Tan, M.J. Sobkowicz, Effects of chain-extending stabilizer on bioplastic poly(lactic acid)/polyamide blends compatibilized by reactive extrusion, Polym. Degrad. Stab. 153 (2018) 118–129, doi:10.1016/J. POLYMDEGRADSTAB.2018.03.020.
- [100] T. Zhang, W. Han, C. Zhang, Y. Weng, Effect of chain extender and light stabilizer on the weathering resistance of PBAT/PLA blend films prepared by extrusion blowing, Polym. Degrad. Stab. 183 (2021) 109455, doi:10.1016/J. POLYMDEGRADSTAB.2020.109455.
- [101] A. Przybytek, M. Sienkiewicz, J. Kucińska-Lipka, H. Janik, Preparation and characterization of biodegradable and compostable PLA/TPS/ESO compositions, Ind. Crops Prod. 122 (2018) 375–383, doi:10.1016/J.INDCROP.2018.06.016.
- [102] R. Gallego, S. López-Quintana, F. Basurto, K. Núñez, N. Villarreal, J.C. Merino, Synthesis of new compatibilizers to poly(lactic acid) blends, Polym. Eng. Sci. 54 (2014) 522–530, doi:10.1002/PEN.23589.
- [103] J. Zhan, G. Wang, J. Li, Y. Guan, G. Zhao, H. Naceur, D. Coutellier, J. Lin, Effect of the compatilizer and chemical treatments on the performance of poly(lactic acid)/ramie fiber composites, Compos. Commun. 27 (2021) 100843, doi:10.1016/J.COCO.2021.100843.
- [104] B. Nim, S.S. Rahayu, K. Thananukul, C. Eang, M. Opaprakasit, A. Petchsuk, C. Kaewsaneha, D. Polpanich, P. Opaprakasit, Sizing down and functionalizing polylactide (PLA) resin for synthesis of PLA-based polyurethanes for use in biomedical applications, Sci. Reports 131 (13) (2023) 1–20 (2023), doi:10.1038/s41598-023-29496-x.
- [105] V. DeStefano, S. Khan, A. Tabada, Applications of PLA in modern medicine, Eng. Regen. 1 (2020) 76–87, doi:10.1016/J.ENGREG.2020.08.002.
- [106] V. Lassalle, M.L. Ferreira, PLA nano- and microparticles for drug delivery: an overview of the methods of preparation, Macromol. Biosci. 7 (2007) 767–783, doi:10.1002/MABI.200700022.
- [107] B. Tyler, D. Gullotti, A. Mangraviti, T. Utsuki, H. Brem, Polylactic acid (PLA) controlled delivery carriers for biomedical applications, Adv. Drug Deliv. Rev. 107 (2016) 163–175, doi:10.1016/J.ADDR.2016.06.018.
- [108] R. Mundel, T. Thakur, M. Chatterjee, Emerging uses of PLA-PEG copolymer in cancer drug delivery, 3 Biotech 12 (2022) 1–12, doi:10.1007/ S13205-021-03105-Y/METRICS.
- [109] M. Vert, After soft tissues, bone, drug delivery and packaging, PLA aims at blood, Eur. Polym. J. 68 (2015) 516–525, doi:10.1016/J.EURPOLYMJ.2015.03.051.
- [110] H.C. Nam, W.H. Park, Aliphatic polyester-based biodegradable microbeads for sustainable cosmetics, ACS Biomater. Sci. Eng. 6 (2020) 2440–2449, doi:10.1021/ ACSBIOMATERIALS.0C00017/SUPPL\_FILE/AB0C00017\_SI\_001.PDF.
- [111] M. Connolly, Y. Zhang, D.M. Brown, N. Ortuño, M. Jordá-Beneyto, V. Stone, T.F. Fernandes, H.J. Johnston, Novel polylactic acid (PLA)-organoclay nanocomposite bio-packaging for the cosmetic industry; migration studies and in vitro assessment of the dermal toxicity of migration extracts, Polym. Degrad. Stab. 168 (2019) 108938, doi:10.1016/J.POLYMDEGRADSTAB.2019.108938.
- [112] H.C. Nam, W.H. Park, Eco-friendly poly(lactic acid) microbeads for cosmetics via melt electrospraying, Int. J. Biol. Macromol. 157 (2020) 734–742, doi:10.1016/ J.IJBIOMAC.2019.11.240.
- [113] F. Rancan, D. Papakostas, S. Hadam, S. Hackbarth, T. Delair, C. Primard, B. Verrier, W. Sterry, U. Blume-Peytavi, A. Vogt, Investigation of polylactic acid (PLA) nanoparticles as drug delivery systems for local dermatotherapy, Pharm. Res. 26 (2009) 2027–2036. doi:10.1007/S11095-009-9919-X/METRICS.
- [114] M.N. Abu Hajleh, A. AL-Samydai, E.A.S. Al-Dujaili, Nano, micro particulate and cosmetic delivery systems of polylactic acid: a mini review, J. Cosmet. Dermatol. 19 (2020) 2805–2811, doi:10.1111/JOCD.13696.
- [115] A.K. Trivedi, M.K. Gupta, H. Singh, PLA based biocomposites for sustainable products: a review, Adv. Ind. Eng. Polym. Res. 6 (2023) 382–395, doi:10.1016/J. AIEPR.2023.02.002.
- [116] D. Gere, T. Czigany, Future trends of plastic bottle recycling: compatibilization of

- PET and PLA, Polym. Test. 81 (2020) 106160, doi:10.1016/J.POLYMERTESTING. 2019.106160.
- [117] R. Roy, A. Mukhopadhyay, Tribological studies of 3D printed ABS and PLA plastic parts, Mater. Today Proc 41 (2021) 856–862, doi:10.1016/J.MATPR.2020.09.235.
- [118] E. Tamburini, S. Costa, D. Summa, L. Battistella, E.A. Fano, G. Castaldelli, Plastic (PET) vs bioplastic (PLA) or refillable aluminium bottles – What is the most sustainable choice for drinking water? A life-cycle (LCA) analysis, Environ. Res. 196 (2021) 110974, doi:10.1016/J.ENVRES.2021.110974.
- [119] S. Knoch, F. Pelletier, M. Larose, G. Chouinard, M.J. Dumont, J.R. Tavares, Surface modification of PLA nets intended for agricultural applications, Colloids Surfaces A Physicochem. Eng. Asp. 598 (2020) 124787, doi:10.1016/ J.COLSURFA.2020.124787.
- [120] D.C. França, T.G. Almeida, G. Abels, E.L. Canedo, L.H. Carvalho, R.M.R. Wellen, K. Haag, K. Koschek, Tailoring PBAT/PLA/Babassu films for suitability of agriculture mulch application, J. Nat. Fibers 16 (2019) 933–943, doi:10.1080/ 15440478.2018.1441092.
- [121] M. Mochizuki, Textile applications, poly(Lactic Acid) synth, . Struct. Prop. Process. Appl. End Life (2022) 619–629, doi:10.1002/9781119767480.CH27.
- [122] X. Yang, W. Fan, S. Ge, X. Gao, S. Wang, Y. Zhang, S.Y. Foong, R.K. Liew, S.S. Lam, C. Xia, Advanced textile technology for fabrication of ramie fiber PLA composites with enhanced mechanical properties, Ind. Crops Prod. 162 (2021) 113312. doi:10.1016/j.INDCROP.2021.113312.
- [123] S. Gong, B. Zhang, J. Zhang, Z.L. Wang, K. Ren, Biocompatible poly(lactic acid)-based hybrid piezoelectric and electret nanogenerator for electronic skin applications, Adv. Funct. Mater. 30 (2020) 1908724, doi:10.1002/ADFM. 201908724.
- [124] S. Gupta, S. Sharma, A. Kumar Nadda, M. Saad Bala Husain, A. Gupta, Biopolymers from waste biomass and its applications in the cosmetic industry: a review, Mater. Today Proc 68 (2022) 873–879, doi:10.1016/J.MATPR.2022.06. 422.
- [125] K.K. Guduru, G. Srinivasu, Effect of post treatment on tensile properties of carbon reinforced PLA composite by 3D printing, Mater. Today Proc 33 (2020) 5403–5407, doi:10.1016/J.MATPR.2020.03.128.
- [126] A.G. de Souza, R.F.S. Barbosa, D.S. Rosa, Nanocellulose from industrial and agricultural waste for further use in PLA composites, J. Polym. Environ. 287 (28) (2020) 1851–1868 (2020), doi:10.1007/S10924-020-01731-W.
- [127] G.H. Loh, A. Sotayo, E. Pei, Development and testing of material extrusion additive manufactured polymer–textile composites, Fash. Text. 8 (2021) 1–21, doi:10.1186/S40691-020-00232-7/TABLES/8.
- [128] C. Sun, S. Wei, H. Tan, Y. Huang, Y. Zhang, Progress in upcycling polylactic acid waste as an alternative carbon source: a review, Chem. Eng. J. 446 (2022) 136881, doi:10.1016/J.CEJ.2022.136881.
- [129] A. Uva, A. Lin, J. Babi, H. Tran, Bioderived and degradable polymers for transient electronics, J. Chem. Technol. Biotechnol. 97 (2022) 801–809, doi:10.1002/ JCTB.6790.
- [130] S. Shaikh, M. Yaqoob, P. Aggarwal, An overview of biodegradable packaging in food industry, Curr. Res. Food Sci. 4 (2021) 503–520, doi:10.1016/J.CRFS.2021. 07.005.
- [131] C. Moretti, L. Hamelin, L.G. Jakobsen, M.H. Junginger, M.M. Steingrimsdottir, L. Høibye, L. Shen, Cradle-to-grave life cycle assessment of single-use cups made from PLA, PP and PET, Resour. Conserv. Recycl. 169 (2021) 105508, doi:10.1016/ J.RESCONREC.2021.105508.
- [132] G.Z. Papageorgiou, T. Beslikas, J. Gigis, J. Christoforides, D.N. Bikiaris, Crystallization and enzymatic hydrolysis of PLA grade for orthopedics, Adv. Polym. Technol. 29 (2010) 280–299, doi:10.1002/ADV.20194.
- [133] H. Zhou, J.G. Lawrence, S.B. Bhaduri, Fabrication aspects of PLA-CaP/PLGA-CaP composites for orthopedic applications: a review, Acta Biomater 8 (2012) 1999– 2016, doi:10.1016/J.ACTBIO.2012.01.031.
- [134] N.İ. Büyük, D. Aksu, G.Torun Köse, Effect of different pore sizes of 3D printed PLA-based scaffold in bone tissue engineering, Int. J. Polym. Mater. Polym. Biomater. 72 (2023) 1021–1031, doi:10.1080/00914037.2022.2075869.
- [135] I. Gendviliene, E. Simoliunas, S. Rekstyte, M. Malinauskas, L. Zaleckas, D. Jegelevicius, V. Bukelskiene, V. Rutkunas, Assessment of the morphology and dimensional accuracy of 3D printed PLA and PLA/HAp scaffolds, J. Mech. Behav. Biomed. Mater. 104 (2020) 103616, doi:10.1016/J.JMBBM.2020.103616.
- [136] J.W. Li, C.F. Du, C.X. Yuchi, C.Q. Zhang, Application of biodegradable materials in orthopedics, J. Med. Biol. Eng. 39 (2019) 633–645, doi:10.1007/ S40846-019-00469-8/TABLES/12.
- [137] P. Feng, J. Jia, M. Liu, S. Peng, Z. Zhao, C. Shuai, Degradation mechanisms and acceleration strategies of poly (lactic acid) scaffold for bone regeneration, Mater. Des. 210 (2021) 110066, doi:10.1016/J.MATDES.2021.110066.
- [138] M. Hussain, S.M. Khan, K. Al-Khaled, M. Ayadi, N. Abbas, W. Chammam, Performance analysis of biodegradable materials for orthopedic applications, Mater. Today Commun. 31 (2022) 103167, doi:10.1016/J.MTCOMM.2022. 103167
- [139] D.A. Houston, A.K. Amin, T.O. White, I.D.M. Smith, A.C. Hall, Chondrocyte death after drilling and articular screw insertion in a bovine model, Osteoarthr. Cartil. 21 (2013) 721–729, doi:10.1016/J.JOCA.2013.02.001.
- [140] S. Rhatomy, L. Hartoko, R. Setyawan, N.R. Soekarno, A.I. Zainal Asikin,

- D. Pridianto, E. Mustamsir, Single bundle ACL reconstruction with peroneus longus tendon graft: 2-years follow-up, J. Clin. Orthop. Trauma 11 (2020) S332–S336. doi:10.1016/J.ICOT.2019.09.004.
- [141] R. Setyawan, N.R. Soekarno, A.I.Z. Asikin, S. Rhatomy, Posterior Cruciate Ligament reconstruction with peroneus longus tendon graft: 2-years follow-up, Ann. Med. Surg. 43 (2019) 38–43, doi:10.1016/J.AMSU.2019.05.009.
- [142] S. Perelli, F. Ibañez, P.E. Gelber, J.I. Erquicia, X. Pelfort, J.C. Monllau, Selective bundle reconstruction in partial ACL tears leads to excellent long-term functional outcomes and a low percentage of failures, Knee 26 (2019) 1262– 1270, doi:10.1016/J.KNEE.2019.09.001.
- [143] K. Ueki, K. Okabe, A. Moroi, K. Marukawa, M. Sotobori, Y. Ishihara, K. Nakagawa, Maxillary stability after Le Fort I osteotomy using three different plate systems, Int. J. Oral Maxillofac. Surg. 41 (2012) 942–948, doi:10.1016/J.IJOM.2012.02. 023
- [144] K. Ueki, A. Moroi, A. Takayama, T. Tsutsui, Y. Saito, K. Yoshizawa, Evaluation of border movement of the mandible before and after orthognathic surgery using a kinesiograph, J. Cranio-Maxillofacial Surg. 48 (2020) 477–482, doi:10.1016/J. ICMS.2020.02.021.
- [145] M. Kokkinakis, A. Ashmore, M. El-Guindi, Intraoperative complications using the Bio-Transfix femoral fixation implant in anterior cruciate ligament reconstruction, Arch. Orthop. Trauma Surg. 130 (2010) 375–379, doi:10.1007/ S00402-009-0976-8/METRICS.
- [146] N.H. Choi, S.Y. Yoo, B.N. Victoroff, Tibial tunnel widening after hamstring anterior cruciate ligament reconstructions: comparison between Rigidfix and bio-Transfix, Knee 20 (2013) 31–35, doi:10.1016/J.KNEE.2012.05.009.
- [147] M.E. Hantes, Z. Dailiana, V.C. Zachos, S.E. Varitimidis, Anterior cruciate ligament reconstruction using the Bio-TransFix femoral fixation device and anteromedial portal technique, Knee Surgery, Sport. Traumatol. Arthrosc. 14 (2006) 497–501, doi:10.1007/S00167-005-0705-Y/METRICS.
- [148] S. Ogino, N. Morimoto, M. Sakamoto, C. Jinno, K. Yoshikawa, T. Enoshiri, Y. Sakamoto, T. Taira, S. Suzuki, Development of a novel bioabsorbable implant that is substituted by adipose tissue in vivo, J. Tissue Eng. Regen. Med. 12 (2018) 633–641, doi:10.1002/TERM.2482.
- [149] M. Ando, Effect of internal fixation of the sternum using bioabsorbable pins in small children, J. Card. Surg. 34 (2019) 983–987, doi:10.1111/JOCS.14174.
- [150] M. Werner, A. Micari, A. Cioppa, G. Vadalà, A. Schmidt, H. Sievert, P. Rubino, A. Angelini, D. Scheinert, G. Biamino, Evaluation of the biodegradable Peripheral Igaki-Tamai Stent in the treatment of De Novo Lesions in the superficial femoral artery: the GAIA study, JACC Cardiovasc. Interv. 7 (2014) 305–312, doi:10.1016/J.JCIN.2013.09.009.
- [151] M. Werner, A. Schmidt, S. Scheinert, U. Banning-Eichenseer, M. Ulrich, Y. Bausback, S. Steiner, D. Scheinert, Evaluation of the biodegradable Igaki-Tamai scaffold after drug-eluting balloon treatment of de novo superficial femoral artery lesions, http://doi.org/10.1177/1526602815620618 23 (2015) 92–97.
- [152] M. Costanzi, A. Saro, S. Bocquet, T.M.C. Abbott, M. Aguena, S. Allam, A. Amara, J. Annis, S. Avila, D. Bacon, B.A. Benson, S. Bhargava, D. Brooks, E. Buckley-Geer, D.L. Burke, A. Carnero Rosell, M. Carrasco Kind, J. Carretero, A. Choi, L.N. Da Costa, M.E.S. Pereira, J. De Vicente, S. Desai, H.T. Diehl, J.P. Dietrich, P. Doel, T.F. Eifler, S. Everett, I. Ferrero, A. Ferté, B. Flaugher, P. Fosalba, J. Frieman, J. García-Bellido, E. Gaztanaga, D.W. Gerdes, T. Giannantonio, P. Giles, S. Grandis, D. Gruen, R.A. Gruendl, N. Gupta, G. Gutierrez, W.G. Hartley, S.R. Hinton, D.L. Hollowood, K. Honscheid, D.J. James, T. Jeltema, E. Krause, K. Kuehn, N. Kuropatkin, O. Lahav, M. Lima, N. MacCrann, M.A.G. Maia, J.L. Marshall, F. Menanteau, R. Miquel, J.J. Mohr, R. Morgan, J. Myles, R.L.C. Ogando, A. Palmese, F. Paz-Chinchón, A.A. Plazas, D. Rapetti, C.L. Reichardt, A.K. Romer, A. Roodman, F. Ruppin, L. Salvati, S. Samuroff, E. Sanchez, V. Scarpine, S. Serrano, I. Sevilla-Noarbe, P. Singh, M. Smith, M. Soares-Santos, A.A. Stark, E. Suchyta, M.E.C. Swanson, G. Tarle, D. Thomas, C. To, D.L. Tucker, T.N. Varga, R.H. Wechsler, Z. Zhang, Cosmological constraints from des Y1 cluster abundances and SPT multiwavelength data, Phys. Rev. D 103 (2021) 043522, doi:10.1103/PHYSREVD.103.043522/FIGURES/13/MEDIUM.
- [153] H. Nef, J. Wiebe, N. Boeder, O. Dörr, T. Bauer, K.E. Hauptmann, A. Latib, A. Colombo, D. Fischer, T. Rudolph, N. Foin, G. Richardt, C. Hamm, A multicenter post-marketing evaluation of the Elixir DESolve® Novolimus-eluting bioresorbable corosnary scaffold system: first results from the DESolve PMCF study, Catheter. Cardiovasc. Interv. 92 (2018) 1021–1027, doi:10.1002/CCD.27550.
- [154] G. Barreira, J.R. Costa, R. Costa, R. Staico, D. Chamie, J.R. Slhessarenko, L.F. Tanajura, A. Abizaid, A. Sousa, A. Abizaid, Serial intravascular ultrasound evaluation of the DESolve™ novolimus-eluting bioresorbable coronary scaffold system, Catheter. Cardiovasc. Interv. 92 (2018) E368–E374, doi:10.1002/CCD. 27591.
- [155] H.M. Gunes, T. Gokdeniz, F. Kizilirmak Yilmaz, G.G. Demir, E. Guler, G. Babur Guler, O. Karaca, B. Cakal, M.O. Omaygenç, E. İbişoğlu, B. Boztosun, Real-life data regarding acute procedural success and 1-year clinical outcome of desolve bioresorbable scaffolds, J. Interv. Cardiol. 30 (2017) 189–194, doi:10.1111/JOIC. 12386
- [156] K. Takahashi, Y. Katagiri, M. Tomaniak, P. Chichareon, R. Modolo, N. Kogame, C.C. Chang, M. Ono, H. Kawashima, C. Gao, N. Bullett, N. Ahmed, K. Al-Lamee, R. Al-Lamee, P. Serruys, Y. Onuma, TCT-186 preclinical evaluation of a novel thin-strut PLLA bioresorbable scaffold in porcine coronary artery at 6-month

- follow-up, J. Am. Coll. Cardiol. 74 (2019) B185, doi:10.1016/J.JACC.2019.08.
- [157] R. Al-Lamee, ArterioSorb<sup>TM</sup> bioresorbable scaffold by Arterius Ltd, Bioresorb. Scaffolds (2017) 503–508, doi:10.1201/9781315380629-62.
- [158] E. Tenekecioglu, R. Torii, C.V. Bourantas, R. Cavalcante, Y. Sotomi, Y. Zeng, C. Collet, T. Crake, A. Abizaid, Y. Onuma, S. Su, T. Santoso, P.W. Serruys, Hemodynamic analysis of a novel bioresorbable scaffold in porcine coronary artery model, Catheter. Cardiovasc. Interv. 91 (2018) 1084–1091, doi:10.1002/CCD.27253.
- [159] E. Tenekecioglu, Y. Sotomi, R. Torii, C. Bourantas, Y. Miyazaki, C. Collet, T. Crake, S. Su, Y. Onuma, P.W. Serruys, Strut protrusion and shape impact on endothelial shear stress: insights from pre-clinical study comparing Mirage and Absorb bioresorbable scaffolds, Int. J. Cardiovasc. Imaging 33 (2017) 1313–1322, doi:10. 1007/S10554-017-1124-0/FIGURES/6.
- [160] B. Xu, C. Guan, R. Gao, TCT-428 a first-in-man study of the firesorb sirolimus target eluting bioresorbable vascular scaffold in patients with coronary artery disease (FUTURE-I): two-year clinical and imaging outcomes, J. Am. Coll. Cardiol. 72 (2018) B172–B173, doi:10.1016/J.JACC.2018.08.1593.
- [161] W. Cai, E. Chen, X. Zeng, C. Chen, L. Wu, X. Zheng, L. Chen, Efficacy and biosafety of a new bioresorbable vascular scaffold covered with biodegradable film in rabbits: an in vivo study, Acta Cardiol. Sin. 36 (2020) 660, doi:10.6515/ ACS.202011\_36(6).20200421B.
- [162] M. Ortega, P. Quiñonez, M. Medrano, C. Chavez, E. Del Pino, J. Costa, TCT-388 real world follow- up one year of the novel MeRes100, J. Am. Coll. Cardiol. 72 (2018) B157, doi:10.1016/J.JACC.2018.08.1545.
- [163] A. Seth, B. Ezhumalai, S. Bhatt, P. Vasani, MeRes100TM—a sirolimus eluting bioresorbable vascular scaffold system, Bioresorb. Scaffolds (2017) 494–499, doi:10.1201/9781315380629-59.
- [164] Y. Han, B. Xu, G. Fu, X. Wang, K. Xu, C. Jin, L. Tao, L. Li, Y. Hou, X. Su, Q. Fang, L. Chen, H. Liu, B. Wang, Z. Yuan, C. Gao, S. Zhou, Z. Sun, Y. Zhao, C. Guan, G.W. Stone, A randomized trial comparing the neovas sirolimus-eluting bioresorbable scaffold and metallic everolimus-eluting stents, JACC Cardiovasc. Interv. 11 (2018) 260–272, doi:10.1016/J.JCIN.2017.09.037.
- [165] Y. Wu, J. Yin, J. Chen, Z. Yao, J. Qian, L. Shen, L. Ge, J. Ge, Final report of the 5-year clinical outcomes of the XINSORB bioresorbable sirolimus-eluting scaffold in the treatment of single de novo coronary lesions in a first-in-human study, Ann. Transl. Med. 8 (2020) 1162 –1162, doi:10.21037/ATM-20-5668.
- [166] Y. Wu, Z. Yao, J. Yin, J. Chen, J. Qian, L. Shen, L. Ge, J. Ge, on behalf of the XINSORB randomized clinical trial, Three-year clinical outcomes of a sirolimus-eluting bioresorbable scaffold (XINSORB) and a metallic stent to treat coronary artery stenosis, Ann. Transl. Med. 8 (2020) 1489 –1489, doi:10.21037/ ATM-20-6739
- [167] X. Lv, L. Shen, Y. Wu, L. Ge, J. Chen, J. Yin, R. Wang, M. Ji, B. Hong, J. Ge, Healing score of the Xinsorb scaffold in the treatment of de novo lesions: 6month imaging outcomes, Int. J. Cardiovasc. Imaging 34 (2018) 1009–1016, doi:10.1007/S10554-018-1326-0/METRICS.
- [168] Y. Wu, L. Shen, J. Yin, J. Chen, J. Qian, L. Ge, J. Ge, Twelve-month angiographic and clinical outcomes of the XINSORB bioresorbable sirolimus-eluting scaffold and a metallic stent in patients with coronary artery disease, Int. J. Cardiol. 293 (2019) 61–66, doi:10.1016/J.IJCARD.2019.06.053.
- [169] Y. Wu, L. Shen, L. Ge, Q. Wang, J. Qian, F. Zhang, K. Yao, D. Huang, Y. Chen, J. Ge, Six-month outcomes of the XINSORB bioresorbable sirolimus-eluting scaffold in treating single de novo lesions in human coronary artery, Catheter. Cardiovasc. Interv. 87 (2016) 630–637, doi:10.1002/CCD.26404.
- [170] S. Yu, M. Wang, M. Yan, B. Wang, Y. Xu, Dynamic changes in inflammatory responses and 3-year clinical outcomes of XINSORB scaffolds in coronary stenting, Cardiovasc. Revasculariz. Med. (2023), doi:10.1016/J.CARREV.2023.10. 020
- [171] S. Yu, M. Wang, M. Yan, B. Wang, Y. Xu, Impact of the Xinsorb Scaffold-related parameters on platelet reactivity in patients with single de novo coronary artery lesions undergoing clopidogrel treatment, Anatol. J. Cardiol. 27 (2023) 408, doi:10.14744/ANATOLJCARDIOL.2023.3071.
- [172] J.J. Costi, A.J. Kelly, T.C. Hearn, D.K. Martin, Comparison of torsional strengths of bioabsorbable screws for anterior cruciate ligament reconstruction\*, 29 (2001) 575–580. https://doi.org/10.1177/03635465010290050901.
- [173] T. Jayamoorthy, J.R. Field, J.J. Costi, D.K. Martin, R.M. Stanley, T.C. Hearn, Biceps tenodesis: a biomechanical study of fixation methods, J. Shoulder Elb. Surg. 13 (2004) 160–164, doi:10.1016/J.JSE.2003.12.001.
- [174] W. Wirth, R.B. Frobell, R.B. Souza, X. Li, B.T. Wyman, M.P. Hellio Le Graverand, T.M. Link, S. Majumdar, F. Eckstein, A three-dimensional quantitative method to measure meniscus shape, position, and signal intensity using MR images: a pilot study and preliminary results in knee osteoarthritis, Magn. Reson. Med. 63 (2010) 1162–1171, doi:10.1002/MRM.22380.
- [175] T. Zantop, A.K. Eggers, V. Musahl, A. Weimann, J. Hassenpflug, W. Petersen, A new rigid biodegradable anchor for meniscus refixation: biomechanical evaluation, Knee Surgery, Sport Traumatol. Arthrosc. 12 (2004) 317–324, doi:10. 1007/S00167-003-0439-7/METRICS.
- [176] P.R. Kurzweil, C.D. Tifford, E.M. Ignacio, Unsatisfactory clinical results of meniscal repair using the meniscus arrow, Arthrosc. J. Arthrosc. Relat. Surg. 21 (2005) e1-905.e7, doi:10.1016/J.ARTHRO.2005.06.002.

- [177] J. Fajadet, M.G. Mennuni, D. Carrié, P. Barragan, P. Coste, M. Vert, A. Lafont, First-in-Man trial of a drug-free bioresorbable stent designed to minimize the duration of coronary artery scaffolding, J. Biomater. Sci. Polym. Ed. 32 (2021) 1251–1266, doi:10.1080/09205063.2021.1910919.
- [178] K. Yahagi, Y. Yang, S. Torii, J. Mensah, R.M. White, M. Mathieu, E. Pacheco, M. Nakano, A. Barakat, T. Sharkawi, M. Vert, M. Joner, A.V. Finn, R. Virmani, A. Lafont, Comparison of a drug-free early programmed dismantling PDLLA bioresorbable scaffold and a metallic stent in a porcine coronary artery model at 3-year follow-up, J. Am. Heart Assoc. 6 (2017), doi:10.1161/JAHA.117.005693.
- [179] R. Plavec, S. Hlaváčiková, L. Omaníková, J. Feranc, Z. Vanovčanová, K. Tomanová, J. Bočkaj, J. Kruželák, E. Medlenová, I. Gálisová, L. Danišová, R. Příkryl, S. Figalla, V. Melčová, P. Alexy, Recycling possibilities of bioplastics based on PLA/PHB blends, Polym. Test. 92 (2020) 106880, doi:10.1016/J. POLYMERTESTING.2020.106880.
- [180] D. Briassoulis, I.G. Athanasoulia, P. Tserotas, PHB/PLA plasticized by olive oil and carvacrol solvent-cast films with optimised ductility and physical ageing stability, Polym. Degrad. Stab. 200 (2022) 109958, doi:10.1016/J. POLYMDEGRADSTAB.2022.109958.
- [181] L. Miao, W.C. Walton, L. Wang, L. Li, Y. Wang, Characterization of polylactic acids-polyhydroxybutyrate based packaging film with fennel oil, and its application on oysters, Food Packag. Shelf Life 22 (2019) 100388, doi:10.1016/ J.FPSL.2019.100388.
- [182] V. Kumar, R. Sehgal, R. Gupta, Blends and composites of polyhydroxyalkanoates (PHAs) and their applications, Eur. Polym. J. 161 (2021) 110824, doi:10.1016/J. EURPOLYMI.2021.110824.
- [183] Y. Zhong, P. Godwin, Y. Jin, H. Xiao, Biodegradable polymers and green-based antimicrobial packaging materials: a mini-review, Adv. Ind. Eng. Polym. Res. 3 (2020) 27–35, doi:10.1016/J.AIEPR.2019.11.002.
- [184] N. Gürler, G. Torğut, Dielectric biodegradable biopolymer-based graphene nanocomposites for use in the packaging industry and capacitor application, ChemistrySelect 7 (2022) e202201975, doi:10.1002/SLCT.202201975.
- [185] M. Asgher, S.A. Qamar, M. Bilal, H.M.N. Iqbal, Bio-based active food packaging materials: sustainable alternative to conventional petrochemicalbased packaging materials, Food Res. Int. 137 (2020) 109625, doi:10.1016/J. FOODRES.2020.109625.
- [186] G. Torğut, N. Gürler, Nanofiller reinforced biodegradable PHA/PLA composites: physico-chemical, thermal and dielectric properties, J. Polym. Res. 28 (2021) 1– 11, doi:10.1007/S10965-021-02816-3/TABLES/4.
- [187] T. Zhao, J. Yu, X. zhang, W. Han, S. zhang, H. Pan, Q. Zhang, X. Yu, J. Bian, H. Zhang, Thermal, crystallization, and mechanical properties of polylactic acid (PLA)/poly(butylene succinate) (PBS) blends, Polym. Bull. (2023) 1–24, doi:10.1007/S00289-023-04848-9/TABLES/4.
- [188] P.A. Kothavade, P. Yadav, A.D. Nidhankar, A. Torris, H. Pol, A. Kafi, S. Bateman, S.B. Sukumaran, K. Shanmuganathan, Luminescent 3D printed poly(lactic acid) nanocomposites with enhanced mechanical properties, Polym. Eng. Sci. 63 (2023) 2059–2072, doi:10.1002/PEN.26345.
- [189] J. Hou, G. Zhou, J. Hu, Y. Wang, S. Gao, Preparation and evaluation of PLA/PVP core-shell microparticles mat via single capillary electrospraying as a potential drug-loading material, Polym. Bull. 79 (2022) 2173–2188, doi:10.1007/ S00289-021-03613-0/FIGURES/7.
- [190] G. Yakub, A. Toncheva, V. Kussovski, R. Toshkova, A. Georgieva, E. Nikolova, N. Manolova, I. Rashkov, Curcumin-PVP loaded electrospun membranes with conferred antibacterial and antitumoral activities, Fibers Polym 21 (2020) 55–65, doi:10.1007/S12221-020-9473-Z/METRICS.
- [191] A. Chabane, F. Bouchal, M. Hentabli, N. Ayachi, H.E. Slama, F. Rezgui, L. Hammoumraoui, Investigation of the candesartan cilexetil antihypertensive drug microencapsulation by PLA-PVP K30 biodegradable polymers: experimental optimization and release kinetics modelling, Can. J. Chem. Eng. 101 (2023) 4446–4459, doi:10.1002/CJCE.24811.
- [192] R.L. Gil, C.G. Amorim, J.M. Rodríguez-Díaz, A.N. Araújo, M.C.B.S.M. Montenegro, Nanofibers in Medical Microbiology (2021) 87– 117, doi:10.1007/978-981-15-9916-3\_4.
- [193] R. Jain, S. Shetty, K.S. Yadav, Unfolding the electrospinning potential of biopolymers for preparation of nanofibers, J. Drug Deliv. Sci. Technol. 57 (2020) 101604, doi:10.1016/J.JDDST.2020.101604.
- [194] H. Zhou, Y. Xia, G. Mu, Y. Gao, S. Liang, G. Li, Q. Yang, X. Lin, F. Qian, The preparation and characterization of biodegradable PCL/PLA shape memory blends, J. Macromol. Sci. Part A 58 (2021) 669–676, doi:10.1080/10601325.2021. 1921598.
- [195] Y. Wang, Y. Wang, Q. Wei, J. Zhang, M. Lei, M. Li, D. Li, Effects of the composition ratio on the properties of PCL/PLA blends: a kind of thermosensitive shape memory polymer composites, J. Polym. Res. 28 (2021) 1–13, doi:10.1007/S10965-021-02815-4/TABLES/5.
- [196] S. Singh, G. Singh, C. Prakash, S. Ramakrishna, L. Lamberti, C.I. Pruncu, 3D printed biodegradable composites: an insight into mechanical properties of PLA/chitosan scaffold, Polym. Test. 89 (2020) 106722.
- [197] H. Jeong, J. Rho, J.Y. Shin, D.Y. Lee, T. Hwang, K.J. Kim, Mechanical properties and cytotoxicity of PLA/PCL films, Biomed. Eng. Lett. 8 (2018) 267, doi:10.1007/ S13534-018-0065-4.

- [198] A.S. Luyt, I. Kelnar, Effect of blend ratio and nanofiller localization on the thermal degradation of graphite nanoplatelets-modified PLA/PCL, J. Therm. Anal. Calorim. 136 (2019) 2373–2382, doi:10.1007/S10973-018-7870-Y/ TABLES/2.
- [199] J. Oztemur, S. Ozdemir, H. Tezcan-Unlu, G. Cecener, H. Sezgin, I. Yalcin-Enis, Investigation of biodegradability and cellular activity of PCL/PLA and PCL/PLLA electrospun webs for tissue engineering applications, Biopolymers 114 (2023) e23564, doi:10.1002/BIP.23564.
- [200] T. Abudula, U. Saeed, A. Memic, K. Gauthaman, M.A. Hussain, H. Al-Turaif, Electrospun cellulose Nano fibril reinforced PLA/PBS composite scaffold for vascular tissue engineering, J. Polym. Res. 26 (2019) 1–15, doi:10.1007/ S10965-019-1772-Y/FIGURES/11.
- [201] J. Li, P. Jiang, J. Yang, Q. Zhang, H. Chen, Z. Wang, C. Liu, T. Fan, L. Cao, J. Sui, Self-reinforced PTLG copolymer with shish kebab structures and a bionic surface as bioimplant materials for tissue engineering applications, ACS Appl. Mater. Interfaces (2024), doi:10.1021/ACSAMI.3C18093.
- [202] N. Mayilswamy, B. Kandasubramanian, Green composites prepared from soy protein, polylactic acid (PLA), starch, cellulose, chitin: a review, Emergent Mater 53 (5) (2022) 727–753 (2022), doi:10.1007/S42247-022-00354-2.
- [203] P.A.V. Freitas, C. González-Martínez, A. Chiralt, Using rice straw fractions to develop reinforced, active PLA-starch bilayers for meat preservation, Food Chem 405 (2023) 134990, doi:10.1016/J.FOODCHEM.2022.134990.
- [204] J. Mao, Y. Tang, R. Zhao, Y. Zhou, Z. Wang, Preparation of nanofibrillated cellulose and application in reinforced PLA/starch nanocomposite film, J. Polym. Environ. 27 (2019) 728–738, doi:10.1007/S10924-019-01382-6/ FIGURES/12.
- [205] P. Wang, Z.Y. Xiong, H. Xiong, J. Cai, Synergistic effects of modified TiO2/multifunctionalized graphene oxide nanosheets as functional hybrid nanofiller in enhancing the interface compatibility of PLA/starch nanocomposites, J. Appl. Polym. Sci. 137 (2020) 49094, doi:10.1002/APP.49094.
- [206] N. Noivoil, R. Yoksan, Oligo(lactic acid)-grafted starch: a compatibilizer for poly(lactic acid)/thermoplastic starch blend, Int. J. Biol. Macromol. 160 (2020) 506–517, doi:10.1016/J.IJBIOMAC.2020.05.178.
- [207] A. Paydayesh, F. Pashaei Soorbaghi, A. Aref Azar, A. Jalali-Arani, Electrical conductivity of graphene filled PLA/PMMA blends: experimental investigation and modeling, Polym. Compos. 40 (2019) 704–715, doi:10.1002/PC.24722.
- [208] J. Chai, G. Wang, J. Zhao, A. Zhang, Z. Shi, C. Wei, G. Zhao, Microcellular PLA/PMMA foam fabricated by CO2 foaming with outstanding shape-memory performance, J. CO2 Util. 49 (2021) 101553, doi:10.1016/J.JCOU.2021.101553.
- [209] E.Z.E. Zawawi, A.H.N. Hafizah, A.Z. Romli, N.Y. Yuliana, N.N. Bonnia, Effect of nanoclay on mechanical and morphological properties of poly(lactide) acid (PLA) and polypropylene (PP) blends, Mater. Today Proc 46 (2021) 1778–1782, doi:10.1016/J.MATPR.2020.07.612.
- [210] M.Z. Rahman, M. Rahman, T. Mahbub, M. Ashiquzzaman, S. Sagadevan, M.E. Hoque, Advanced biopolymers for automobile and aviation engineering applications, J. Polym. Res. 30 (2023) 1–16, doi:10.1007/S10965-023-03440-Z/ FIGURES/8.
- [211] N. Angin, M. Ertas, S. Caylak, M.S. Fidan, Thermal and electrical behaviors of activated carbon-filled PLA/PP hybrid biocomposites, Sustain. Mater. Technol. 37 (2023) e00655, doi:10.1016/J.SUSMAT.2023.E00655.
- [212] N. Tripathi, M. Misra, A.K. Mohanty, Durable polylactic acid (PLA)-based sustainable engineered blends and biocomposites: recent developments, challenges, and opportunities, ACS Eng. Au 1 (2021) 7–38, doi:10.1021/ ACSENGINEERINGAU.1C00011.
- [213] J. Hun Park, J. Woo Jung, H.W. Kang, Z. Ge, X. Li, D. Si, Research on the preparation and properties of biodegradable wood-plastic composites, IOP Conf. Ser. Mater. Sci. Eng. 892 (2020) 012018, doi:10.1088/1757-899X/892/1/012018.
- [214] M. Cvek, U.C. Paul, J. Zia, G. Mancini, V. Sedlarik, A. Athanassiou, Biodegradable films of PLA/PPC and curcumin as packaging materials and smart indicators of food spoilage, ACS Appl. Mater. Interfaces 14 (2022) 14654–14667, doi:10.1021/ ACSAMI.2C02181/ASSET/IMAGES/LARGE/AM2C02181\_0010, PEG.
- [215] M. Xia, K. Shi, M. Zhou, Y. Shen, T. Wang, Effects of chain extender and uniaxial stretching on the properties of PLA/PPC/mica composites, Polym. Adv. Technol. 30 (2019) 2436–2446, doi:10.1002/PAT.4691.
- [216] Y. Zhang, T. Sun, D. Zhang, S. Sun, J. Liu, B. Li, Z. Shi, Preparation of controllable micro-nano fiber bundle asymmetric porous PLA-PPC ethyl acetate driving film by pre-freezing treatment, Chem. Eng. J. 469 (2023) 143959, doi:10.1016/J.CEJ. 2023.143959.
- [217] Y. Zhang, T. Sun, D. Zhang, S. Sun, J. Liu, B. Li, W. Zhu, Z. Shi, Study of a multiple responses, high deformation, and programmable PLA-PPC/PVA-PDA actuator, Macromol. Rapid Commun. 44 (2023) 2300327, doi:10.1002/MARC. 202300327.
- [218] I.N.H.M. Haneef, Y.F. Buys, N.M. Shaffiar, A.M. Abdul Hamid, S.I.S. Shaharuddin, Fitriani, Composition optimization of PLA/PPC/HNT nanocomposites for mandibular fixation plate using single-factor experimental design, J. Mech. Behav. Biomed. Mater. 135 (2022) 105423, doi:10.1016/J.JMBBM.2022.105423.
- [219] K.V. Aleksanyan, S.Z. Rogovina, N.E. Ivanushkina, Novel biodegradable low-density polyethylene–poly(lactic acid)–starch ternary blends, Polym. Eng. Sci. 61 (2021) 802–809, doi:10.1002/PEN.25624.

- [220] I. Cantón, R. Mckean, M. Charnley, K.A. Blackwood, C. Fiorica, A.J. Ryan, S. MacNeil, Development of an Ibuprofen-releasing biodegradable PLA/PGA electrospun scaffold for tissue regeneration, Biotechnol. Bioeng. 105 (2010) 396– 408, doi:10.1002/BIT.22530.
- [221] D. Liu, Q. Xie, Z. Liu, J. Chen, X. Zou, B. Jing, Improvement of melt viscosity and compatibility of polyglycolic acid (PGA)/polylactic acid (PLA) blend via reactive blending with bifunctional and multifunctional hybrid chain extender, J. Appl. Polym. Sci. 140 (2023) 1–11, doi:10.1002/APP.54501.
- [222] D. Yan, Z. Wang, Z. Guo, Y. Ma, C. Wang, H. Tan, Y. Zhang, Study on the properties of PLA/PBAT composite modified by nanohydroxyapatite, J. Mater. Res. Technol. 9 (2020) 11895–11904, doi:10.1016/J.JMRT.2020.08.062.
- [223] S. Khatsee, D. Daranarong, W. Punyodom, P. Worajittiphon, Electrospinning polymer blend of PLA and PBAT: electrospinnability–solubility map and effect of polymer solution parameters toward application as antibiotic-carrier mats, J. Appl. Polym. Sci. 135 (2018) 46486, doi:10.1002/APP.46486.
- [224] R.C. Rebelo, L.P.C. Gonçalves, A.C. Fonseca, J. Fonseca, M. Rola, J.F.J. Coelho, F. Rola, A.C. Serra, Increased degradation of PLA/PBAT blends with organic acids and derivatives in outdoor weathering and marine environment, Polymer (Guildf) 256 (2022) 125223, doi:10.1016/J.POLYMER.2022.125223.
- [225] N.H.I. Kamaludin, H. Ismail, A. Rusli, S.T. Sam, H. Osman, Evaluation and enhancement of polylactic acid biodegradability in soil by blending with chitosan, J. Polym. Environ. 31 (2023) 2727–2740, doi:10.1007/ S10924-023-02762-9/FIGURES/8.
- [226] M. Song, S. Li, G. Zhu, J. Guo, Compatibilised and toughened of PLA/PCL blends via modified-chitosan linking amorphous regions: 4D printing and shape memory processes, Polym. Test. 125 (2023) 108105, doi:10.1016/J. POLYMERTESTING.2023.108105.
- [227] C. Li, F. Wang, G. Douglas, Z. Zhang, R. Guidoin, L. Wang, Comprehensive mechanical characterization of PLA fabric combined with PCL to form a composite structure vascular graft, J. Mech. Behav. Biomed. Mater. 69 (2017) 39–49, doi:10.1016/J.JMBBM.2016.11.005.
- [228] L. Sartore, N. Inverardi, S. Pandini, F. Bignotti, F. Chiellini, PLA/PCL-based foams as scaffolds for tissue engineering applications, Mater. Today Proc 7 (2019) 410– 417, doi:10.1016/J.MATPR.2018.11.103.
- [229] S. Petisco-Ferrero, A. Etxeberria, J.R. Sarasua, Mechanical properties and state of miscibility in poly(racD,L-lactide-co-glycolide)/(L-lactide-co-e-caprolactone) blends, J. Mech. Behav. Biomed. Mater. 71 (2017) 372–382, doi:10.1016/J. IMBBM.2017.04.003.
- [230] M. Raji, H. Essabir, M. ElAchaby, R. Bouhfid, A.E.K. Qaiss, Morphology control of poly(lactic) acid/polypropylene blend composite by using silanized cellulose fibers extracted from coir fibers, Cellulose 29 (2022) 6759–6782, doi:10.1007/ S10570-022-04675-7/TABLES/6.
- [231] Y. Huang, Y. Jin, B. Wang, H. Tian, Y. Weng, K. Sun, S. Men, Preparation and characterization of compatibilized and toughened polylactic acid/cellulose acetate films by long-chain hyperbranched polymers, J. Appl. Polym. Sci. 139 (2022) 52097. doi:10.1002/APP.52097.
- [232] A. Boarino, A. Schreier, Y. Leterrier, H.A. Klok, Uniformly dispersed poly(lactic acid)-grafted lignin nanoparticles enhance antioxidant activity and UV-barrier properties of poly(lactic acid) packaging films, ACS Appl. Polym. Mater. 4 (2022) 4808–4817, doi:10.1021/ACSAPM.2C00420/ASSET/IMAGES/LARGE/ AP2C00420\_0008.JPEG.
- [233] Y. Yan, L. Zhang, X. Zhao, S. Zhai, Q. Wang, C. Li, X. Zhang, Utilization of lignin upon successive fractionation and esterification in polylactic acid (PLA)/lignin biocomposite, Int. J. Biol. Macromol. 203 (2022) 49–57, doi:10. 1016/J.IJBIOMAC.2022.01.041.
- [234] D.C. Nguyen, A.S. Woo, S.J. Farber, G.B. Skolnick, J. Yu, S.D. Naidoo, K.B. Patel, Comparison of resorbable plating systems: complications during degradation, J. Craniofac. Surg. 28 (2017) 88, doi:10.1097/SCS.0000000000003216.
- [235] W.S. Pietrzak, B.L. Eppley, Stability of craniofacial PLLA/PGA copolymer bioabsorbable screws, J. Craniofac. Surg. 17 (2006) 331–336, doi:10.1097/ 00001665-200603000-00021.
- [236] B.M.P. Ferreira, E.A.R. Duek, Pins composed of poly(L-lactic acid)/poly(3-hydroxybutyrate-co-hydroxyvalerate) PLLA/PHBV blends: degradation in vitro, J. Appl. Biomater. Biomech. 3 (2005) 50–60, doi:10.1177/228080000500300107.
- [237] Y. Srisuwan, Y. Baimark, S. Suttiruengwong, Toughening of poly(L-lactide) with blends of poly( $\epsilon$ -caprolactone- co-l-lactide) in the presence of chain extender, Int. J. Biomater. 2018 (2018), doi:10.1155/2018/1294397.
- [238] Z.S. Tao, X.J. Wu, W.S. Zhou, X. ju Wu, W. Liao, M. Yang, H.G. Xu, L. Yang, Local administration of aspirin with  $\beta$ -tricalcium phosphate/poly-lactic-co-glycolic acid ( $\beta$ -TCP/PLGA) could enhance osteoporotic bone regeneration, J. Bone Miner. Metab. 37 (2019) 1026–1035, doi:10.1007/s00774-019-01008-w.
- [239] Y. Lai, Y. Li, H. Cao, J. Long, X. Wang, L. Li, C. Li, Q. Jia, B. Teng, T. Tang, J. Peng, D. Eglin, M. Alini, D.W. Grijpma, G. Richards, L. Qin, Osteogenic magnesium incorporated into PLGA/TCP porous scaffold by 3D printing for repairing challenging bone defect, Biomaterials 197 (2019) 207–219.
- [240] Z. Hong, P. Zhang, C. He, X. Qiu, A. Liu, L. Chen, X. Chen, X. Jing, Nano-composite of poly(l-lactide) and surface grafted hydroxyapatite: mechanical properties and biocompatibility, Biomaterials 26 (2005) 6296–6304, doi:10.1016/J.BIOMATERIALS.2005.04.018.

- [241] S. Esmaeili, H. Akbari Aghdam, M. Motififard, S. Saber-Samandari, A.H. Montazeran, M. Bigonah, E. Sheikhbahaei, A. Khandan, A porous polymeric-hydroxyapatite scaffold used for femur fractures treatment: fabrication, analysis, and simulation, Eur. J. Orthop. Surg. Traumatol. 301 (30) (2019) 123–131 (2019), doi:10.1007/S00590-019-02530-3.
- [242] Z. Hong, P. Zhang, A. Liu, L. Chen, X. Chen, X. Jing, Composites of poly(lactide-co-glycolide) and the surface modified carbonated hydroxyapatite nanoparticles, J. Biomed. Mater. Res. A 81 (2007) 515–522, doi:10.1002/JBM.A. 31038.
- [243] P. Melo, E. Tarrant, T. Swift, A. Townshend, M. German, A.M. Ferreira, P. Gentile, K. Dalgarno, Short phosphate glass fiber - PLLA composite to promote bone mineralization, Mater. Sci. Eng. C 104 (2019) 109929, doi:10.1016/J.MSEC.2019. 109929
- [244] J. Van Loghem, Y.A. Yutskovskaya, W.M.P. Werschler, Calcium hydroxylapatite over a decade of clinical experience, J. Clin. Aesthet. Dermatol. 8 (2015) 38–49 /pmc/articles/PMC4295857/?report=abstract (accessed January 27, 2021).
- [245] M. Todo, S.D. Park, K. Arakawa, Y. Takenoshita, Relationship between microstructure and fracture behavior of bioabsorbable HA/PLLA composites, Compos. Part A Appl. Sci. Manuf. 37 (2006) 2221–2225, doi:10.1016/j. compositesa.2005.10.001.
- [246] K.C. Ang, K.F. Leong, C.K. Chua, M. Chandrasekaran, Compressive properties and degradability of poly(ε-caprolatone)/hydroxyapatite composites under accelerated hydrolytic degradation, J. Biomed. Mater. Res. - Part A 80 (2007) 655–660, doi:10.1002/jbm.a.30996.
- [247] M. Alizadeh-Osgouei, Y. Li, C. Wen, A comprehensive review of biodegradable synthetic polymer-ceramic composites and their manufacture for biomedical applications, Bioact. Mater. 4 (2019) 22–36, doi:10.1016/j.bioactmat.2018.11. 003.
- [248] M. Dziadek, E. Stodolak-Zych, K. Cholewa-Kowalska, Biodegradable ceramic-polymer composites for biomedical applications: a review, Mater. Sci. Eng. C 71 (2017) 1175–1191, doi:10.1016/j.msec.2016.10.014.
- [249] D. Zhao, T. Zhu, J. Li, L. Cui, Z. Zhang, X. Zhuang, J. Ding, Poly(lactic-co-glycolic acid)-based composite bone-substitute materials, Bioact. Mater. 6 (2021) 346– 360, doi:10.1016/j.bioactmat.2020.08.016.
- [250] I.M. Wojak-Ćwik, Ł. Rumian, M. Krok-Borkowicz, R. Hess, R. Bernhardt, P. Dobrzyński, S. Möller, M. Schnabelrauch, V. Hintze, D. Scharnweber, E. Pamuła, Synergistic effect of bimodal pore distribution and artificial extracellular matrices in polymeric scaffolds on osteogenic differentiation of human mesenchymal stem cells, Mater. Sci. Eng. C 97 (2019) 12–22, doi:10.1016/j.msec.2018.12.012.
- [251] J. Huang, X. Xia, Q. Zou, J. Ma, S. Jin, J. Li, Y. Zuo, Y. Li, The long-term behaviors and differences in bone reconstruction of three polymer-based scaffolds with different degradability, J. Mater. Chem. B 7 (2019) 7690–7703, doi:10.1039/ c9tb02072a.
- [252] J.W. Park, J.U. Hwang, J.H. Back, S.W. Jang, H.J. Kim, P.S. Kim, S. Shin, T. Kim, High strength PLGA/Hydroxyapatite composites with tunable surface structure using PLGA direct grafting method for orthopedic implants, Compos. Part B Eng. 178 (2019) 107449, doi:10.1016/j.compositesb.2019.107449.
- [253] X. Liang, P. Duan, J. Gao, R. Guo, Z. Qu, X. Li, Y. He, H. Yao, J. Ding, Bilayered PLGA/PLGA-HAp composite scaffold for osteochondral tissue engineering and tissue regeneration, ACS Biomater. Sci. Eng. 4 (2018) 3506–3521, doi:10.1021/ acsbiomaterials.8b00552.
- [254] S. Zheng, Y. Guan, H. Yu, G. Huang, C. Zheng, Poly-I-lysine-coated PLGA/poly(amino acid)-modified hydroxyapatite porous scaffolds as efficient tissue engineering scaffolds for cell adhesion, proliferation, and differentiation, New J. Chem. 43 (2019) 9989–10002, doi:10.1039/c9nj01675a.
- [255] Q. Xu, Y. Li, Y. Zhu, K. Zhao, R. Gu, Q. Zhu, Recombinant human BMP-7 grafted poly(lactide-: co -glycolide)/hydroxyapatite scaffolds via polydopamine for enhanced calvarial repair, RSC Adv 8 (2018) 27191–27200, doi:10.1039/ co.ps.65664
- [256] M.S. Namini, N. Bayat, R. Tajerian, S. Ebrahimi-Barough, M. Azami, S. Irani, S. Jangjoo, S. Shirian, J. Ai, A comparison study on the behavior of human endometrial stem cell-derived osteoblast cells on PLGA/HA nanocomposite scaffolds fabricated by electrospinning and freeze-drying methods, J. Orthop. Surg. Res. (2018) 13, doi:10.1186/s13018-018-0754-9.
- [257] N. Deng, J. Sun, Y. Li, L. Chen, C. Chen, Y. Wu, Z. Wang, L. Li, Experimental study of rhBMP-2 chitosan nano-sustained release carrier-loaded PLGA/nHA scaffolds to construct mandibular tissue-engineered bone, Arch. Oral Biol. 102 (2019) 16– 25, doi:10.1016/j.archoralbio.2019.03.023.
- [258] S. Hassanajili, A. Karami-Pour, A. Oryan, T. Talaei-Khozani, Preparation and characterization of PLA/PCL/HA composite scaffolds using indirect 3D printing for bone tissue engineering, Mater. Sci. Eng. C 104 (2019) 109960, doi:10.1016/ I.MSEC.2019.109960.
- [259] Y. Xie, F. Zhang, O. Akkus, M.W. King, A collagen/PLA hybrid scaffold supports tendon-derived cell growth for tendon repair and regeneration, J. Biomed. Mater. Res. Part B Appl. Biomater. 110 (2022) 2624–2635, doi:10.1002/JBM.B. 35116.
- [260] M. Rezai Rad, F. Fahimipour, E. Dashtimoghadam, H. Nokhbatolfoghahaei, L. Tayebi, A. Khojasteh, Osteogenic differentiation of adipose-derived

- mesenchymal stem cells using 3D-Printed PDLLA/ $\beta$ -TCP nanocomposite scaffolds, Bioprinting 21 (2021), doi:10.1016/J.BPRINT.2020.E00117.
- [261] N. Owji, N. Mandakhbayar, J.R. Cha, A.R. Padalhin, Z.K. Erdogan, A. Aldaadaa, T. Shakouri, P. Sawadkar, O. Frost, H.W. Kim, E. García-Gareta, J.C. Knowles, Inclusion of calcium phosphate does not further improve in vitro and in vivo osteogenesis in a novel, highly biocompatible, mechanically stable and 3D printable polymer, Sci. Rep. (2022) 12, doi:10.1038/S41598-022-21013-W.
- [262] W. Wang, B. Zhang, M. Li, J. Li, C. Zhang, Y. Han, L. Wang, K. Wang, C. Zhou, L. Liu, Y. Fan, X. Zhang, 3D printing of PLA/n-HA composite scaffolds with customized mechanical properties and biological functions for bone tissue engineering, Compos. Part B Eng. 224 (2021) 109192, doi:10.1016/J. COMPOSITESB.2021.109192.
- [263] S.V. Harb, E. Kolanthai, A.S. Pugazhendhi, C.A.G. Beatrice, L.A. Pinto, C.J. Neal, E.H. Backes, A.C.C. Nunes, H.S. Selistre-de-Araújo, L.C. Costa, M.J. Coathup, S. Seal, L.A. Pessan, 3D printed bioabsorbable composite scaffolds of poly (lactic acid)-tricalcium phosphate-ceria with osteogenic property for bone regeneration, Biomater. Biosyst. 13 (2024) 100086, doi:10.1016/J.BBIOSY.2023. 100086.
- [264] R. Singh, S.K. Tripathy, M.A. Naik, P. Sujir, S.K. Rao, ACL reconstruction using femoral rigid-fix and tibial Bio-intrafix devices, J. Clin. Orthop. Trauma 8 (2017), doi:10.1016/J.JCOT.2017.06.021.
- [265] C. Rodríguez, T.E. García, S. Montes, L. Rodríguez, A. Maestro, In vitro comparison between cortical and cortico-cancellous femoral suspension devices for anterior cruciate ligament reconstruction: implications for mobilization, Knee Surgery, Sport Traumatol. Arthrosc. 23 (2015) 2324–2329, doi:10.1007/ S00167-014-3055-9/METRICS.
- [266] C.A. Bailey, J.H. Kuiper, C.P. Kelly, Biomechanical evaluation of a new composite bioresorbable screw, J. Hand Surg. Am. 31 (2006) 208–212, doi:10.1016/J.JHSB. 2005.10.015/ASSET/IMAGES/LARGE/10.1016\_J.JHSB.2005.10.015-FIG3.JPEG.
- [267] D. Pérez-Prieto, R. Torres-Claramunt, P.E. Gelber, T.M.A. Shehata, X. Pelfort, J.C. Monllau, Autograft soaking in vancomycin reduces the risk of infection after anterior cruciate ligament reconstruction, Knee Surgery, Sport Traumatol. Arthrosc. 24 (2016) 2724–2728, doi:10.1007/S00167-014-3438-Y/METRICS.
- [268] R. Torres-Claramunt, X. Pelfort, J. Erquicia, S. Gil-González, P.E. Gelber, L. Puig, J.C. Monllau, Knee joint infection after ACL reconstruction: prevalence, management and functional outcomes, Knee Surgery, Sport Traumatol. Arthrosc. 21 (2013) 2844–2849, doi:10.1007/S00167-012-2264-3/METRICS.
- [269] A. Espejo-Baena, A. Espejo-Reina, A. Gómez-Cáceres, M.J. Espejo-Reina, J. Dalla Rosa-Nogales, Associated reconstruction of anterior cruciate and anterolateral ligaments with single asymmetric hamstring tendons graft, Arthrosc. Tech. 6 (2017) e2039–e2046, doi:10.1016/J.EATS.2017.08.002.
- [270] S. Aunoble, D. Clément, P. Frayssinet, M.F. Harmand, J.C. Le Huec, A. S, C. D, F. P, H. MF, L.H. JC, Biological performance of a new beta-TCP/PLLA composite material for applications in spine surgery: in vitro and in vivo studies, J. Biomed. Mater. Res. A 78 (2006) 416–422, doi:10.1002/JBM.A.30749.
- [271] R. Kumar, G. Bharadwaj, M. Kharub, V. Goel, A. Kumar, Performance analysis of nanofluid based direct absorption solar collector of different configurations: a two-phase CFD modeling, (2022). https://doi.org/10.1080/15567036.2022. 2030439.
- [272] J. Satalich, C. Barber, R. O'Connell, Medial patellofemoral ligament reconstruction: a surgical technique to dynamically control graft tension, Arthrosc. Tech. 11 (2022) e2309–e2318, doi:10.1016/J.EATS.2022.08.023.
- [273] A.M. van Gogh, X. Li, G.M. Youn, A. Alvarez, S. Yin, M.O. Chakrabarti, P.J. McGahan, J.L. Chen, Arthroscopic harvesting of autologous bone graft for use as a mesenchymal stem cell carrier in anterior cruciate ligament reconstruction, Arthrosc. Tech. 9 (2020) e45–e50, doi:10.1016/J.EATS.2019.08. 018.
- [274] J.J. Costi, A.J. Kelly, T.C. Hearn, D.K. Martin, C. JJ, K. AJ, H. TC, M. DK, J.J. Costi, A.J. Kelly, T.C. Hearn, D.K. Martin, Comparison of torsional strengths of bioabsorbable screws for anterior cruciate ligament reconstruction, Am. J. Sports Med. 29 (2001) 575–580, doi:10.1177/03635465010290050901.
- [275] S. Pina, J.M.F. Ferreira, Bioresorbable plates and screws for clinical applications: a review, J. Healthc. Eng. 3 (2012) 243–260, doi:10.1260/2040-2295.3.2.243.
- [276] P.G. Ntagiopoulos, G. Demey, T. Tavernier, D. Dejour, Comparison of resorption and remodeling of bioabsorbable interference screws in anterior cruciate ligament reconstruction, Int. Orthop. 39 (2015) 697–706, doi:10.1007/ S00264-014-2530-8.
- [277] M. Chivot, S. Harrosh, F. Kelberine, M. Pithioux, J.N. Argenson, M. Ollivier, Pull-out strength of four tibial fixation devices used in anterior cruciate ligament reconstruction, Orthop. Traumatol. Surg. Res. 104 (2018) 203–207, doi:10.1016/J.OTSR.2017.12.011.
- [278] A. Todor, D.V. Nistor, S. Caterev, Clinical outcomes after ACL reconstruction with free quadriceps tendon autograft versus hamstring tendons autograft. A retrospective study with a minimal follow-up two years, Acta Orthop. Traumatol. Turc. 53 (2019) 180–183, doi:10.1016/J.AOTT.2019.03.004.
- [279] S. Caterev, D.V. Nistor, A. Todor, Anatomic double-bundle anterior cruciate ligament reconstruction with a free quadriceps tendon autograft, Arthrosc. Tech. 5 (2016) e1063–e1067, doi:10.1016/J.EATS.2016.05.015.
- [280] F.A. Barber, W.D. Dockery, Biocomposite interference screws in anterior cruciate

- ligament reconstruction: osteoconductivity and degradation, Arthrosc. Sport. Med. Rehabil. 2 (2020) e53–e58, doi:10.1016/J.ASMR.2019.10.001.
- [281] K.-H.H. Frosch, T. Sawallich, G. Schütze, A. Losch, T. Walde, P. Balcarek, F. Konietschke, K.M. Stürmer, Magnetic resonance imaging analysis of the bioabsorbable Milagro™ interference screw for graft fixation in anterior cruciate ligament reconstruction, Strateg. Trauma Limb Reconstr. 4 (2009) 73, doi:10.1007/S11751-009-0063-2.
- [282] F.A. Barber, W.D. Dockery, S.A. Hrnack, B. FA, D. WD, H. SA, Long-term degradation of a poly-lactide co-glycolide/β-tricalcium phosphate biocomposite interference screw, Arthroscopy 27 (2011) 637–643, doi:10.1016/J.ARTHRO. 2010.11.056.
- [283] J. Vonhoegen, D. John, C. Hägermann, Osteoconductive resorption characteristics of a novel biocomposite suture anchor material in rotator cuff repair, J. Orthop. Surg. Res. (2019) 14, doi:10.1186/S13018-018-1049-X.
- [284] C. Zhao, H. Wu, J. Ni, S. Zhang, X. Zhang, Development of PLA/Mg composite for orthopedic implant: tunable degradation and enhanced mineralization, Compos. Sci. Technol. 147 (2017) 8–15.
- [285] X. Yu, W. Huang, D. Zhao, K. Yang, L. Tan, X. Zhang, J. Li, M. Zhang, S. Zhang, T. Liu, B. Wu, M. Qu, R. Duan, Y. Yuan, Study of engineered low-modulus Mg/PLLA composites as potential orthopaedic implants: an in vitro and in vivo study, Colloids Surf. B Biointerf. 174 (2019) 280–290, doi:10.1016/j.colsurfb. 2018.10.054.
- [286] X.X. Li, Y. Cong, J. Sui, X.X. Li, An investigation on the degradation behaviors of Mg wires/PLA composite for bone fixation implants: influence of wire content and load mode, Sci. Eng. Compos. Mater. 28 (2021) 39–47, doi:10.1515/ SECM-2021-0005/MACHINEREADABLECITATION/RIS.
- [287] Y. Zhang, Y. Yan, X. Xu, Y. Lu, L. Chen, D. Li, Y. Dai, Y. Kang, K. Yu, Investigation on the microstructure, mechanical properties, in vitro degradation behavior and biocompatibility of newly developed Zn-0.8%Li-(Mg, Ag) alloys for guided bone regeneration, Mater. Sci. Eng. C 99 (2019) 1021–1034, doi:10.1016/J.MSEC.2019. 01.120.
- [288] H. Cai, Y. Zhang, X. Li, J. Meng, F. Xue, C. Chu, L. Tao, J. Bai, Self-reinforced biodegradable Mg-2Zn alloy wires/polylactic acid composite for orthopedic implants, Compos. Sci. Technol. 162 (2018) 198–205, doi:10.1016/j.compscitech.2018.04.040.
- [289] J. Lee, H. Lee, K.H. Cheon, C. Park, T.S. Jang, H.E. Kim, H. Do Jung, Fabrication of poly(lactic acid)/Ti composite scaffolds with enhanced mechanical properties and biocompatibility via fused filament fabrication (FFF)-based 3D printing, Addit. Manuf. 30 (2019) 100883, doi:10.1016/J.ADDMA.2019.100883.
- [290] M. Barczewski, A. Hejna, J. Aniśko, J. Andrzejewski, A. Piasecki, O. Mysiukiewicz, M. Bak, B. Gapiński, Z. Ortega, Rotational molding of polylactide (PLA) composites filled with copper slag as a waste filler from metallurgical industry, Polym. Test. 106 (2022) 107449, doi:10.1016/J.POLYMERTESTING. 2021.107449.
- [291] A. Kottasamy, M. Samykano, K. Kadirgama, M. Rahman, M.M. Noor, Experimental investigation and prediction model for mechanical properties of copper-reinforced polylactic acid composites (Cu-PLA) using FDM-based 3D printing technique, Int. J. Adv. Manuf. Technol. 119 (2022) 5211–5232, doi:10. 1007/S00170-021-08289-4/METRICS.
- [292] H. Mehboob, A. Mehboob, F. Abbassi, F. Ahmad, S.H. Chang, Finite element analysis of biodegradable Ti/polyglycolic acid composite bone plates based on 3D printing concept, Compos. Struct. 289 (2022) 115521, doi:10.1016/J. COMPSTRUCT.2022.115521.
- [293] D. Jiang, F. Ning, Y. Wang, Additive manufacturing of biodegradable iron-based particle reinforced polylactic acid composite scaffolds for tissue engineering, J. Mater. Process. Technol. 289 (2021) 116952, doi:10.1016/J.JMATPROTEC.2020. 116952.
- [294] U. Boro, N. Kashyap, V.S. Moholkar, Sonochemical synthesis of poly(lactic acid) nanocomposites with ZnO nanoflowers: effect of nanofiller morphology on physical properties, ACS Eng. Au 2 (2021) 46–60, doi:10.1021/ACSENGINEERINGAU.1C00018.
- [295] M. Heydari-Majd, B. Ghanbarzadeh, M. Shahidi-Noghabi, A. Abdolshahi, S. Dahmardeh, M. Malek Mohammadi, Poly(lactic acid)-based bionanocomposites: effects of ZnO nanoparticles and essential oils on physicochemical properties, Polym. Bull. 79 (2022) 97–119, doi:10.1007/ S00289-020-03490-Z/FIGURES/7.
- [296] I. Restrepo, N. Benito, C. Medinam, R.V. Mangalaraja, P. Flores, S. Rodriguez-Llamazares, Development and characterization of polyvinyl alcohol stabilized polylactic acid/ZnO nanocomposites, Mater. Res. Express 4 (2017) 105019, doi:10.1088/2053-1591/AASB8D.
- [297] C. Swaroop, M. Shukla, Development of blown polylactic acid-MgO nanocomposite films for food packaging, Compos. Part A Appl. Sci. Manuf. 124 (2019) 105482, doi:10.1016/J.COMPOSITESA.2019.105482.
- [298] H. Zhang, M. Hortal, M. Jordá-Beneyto, E. Rosa, M. Lara-Lledo, I. Lorente, ZnO-PLA nanocomposite coated paper for antimicrobial packaging application, LWT 78 (2017) 250–257, doi:10.1016/J.LWT.2016.12.024.
- [299] E. Lizundia, L. Pérez-Álvarez, M. Sáenz-Pérez, D. Patrocinio, J.L. Vilas, L.M. León, Physical aging and mechanical performance of poly(l-lactide)/ZnO nanocomposites, J. Appl. Polym. Sci. (2016) 133, doi:10.1002/APP.43619.
- [300] Z. Tang, F. Fan, Z. Chu, C. Fan, Y. Qin, Barrier properties and characterizations

- of poly(lactic Acid)/ZnO nanocomposites, Molecules (2020) 25, doi:10.3390/MOLECULES25061310.
- [301] R. Pantani, G. Gorrasi, G. Vigliotta, M. Murariu, P. Dubois, PLA-ZnO nanocomposite films: water vapor barrier properties and specific end-use characteristics, Eur. Polym. J. 49 (2013) 3471–3482, doi:10.1016/J.EURPOLYMJ. 2013.08.005.
- [302] R.C. Nonato, L.H.I. Mei, B.C. Bonse, C.V. Leal, C.E. Levy, F.A. Oliveira, C. Delarmelina, M.C.T. Duarte, A.R. Morales, Nanocomposites of PLA/ZnO nanofibers for medical applications: antimicrobial effect, thermal, and mechanical behavior under cyclic stress, Polym. Eng. Sci. 62 (2022) 1147–1155, doi:10.1002/PEN.25913.
- [303] A. Akshaykranth, N. Jayarambabu, T. Venkatappa Rao, R. Rakesh Kumar, L. Srinivasa Rao, Antibacterial activity study of ZnO incorporated biodegradable poly (lactic acid) films for food packaging applications, Polym. Bull. (2022) 1–16, doi:10.1007/S00289-022-04126-0/FIGURES/7.
- [304] Y. Wang, C. Yang, Z. Xin, Y. Luo, B. Wang, X. Feng, Z. Mao, X. Sui, Poly(lactic acid)/carbon nanotube composites with enhanced electrical conductivity via a two-step dispersion strategy, Compos. Commun. 30 (2022) 101087, doi:10.1016/J.COCO.2022.101087.
- [305] M. Keramati, I. Ghasemi, M. Karrabi, H. Azizi, M. Sabzi, Incorporation of surface modified graphene nanoplatelets for development of shape memory PLA nanocomposite, Fibers Polym. 177 (17) (2016) 1062–1068 (2016), doi:10.1007/ S12221-016-6329-7.
- [306] M.H. Al-Saleh, M.M. Al-Sharman, Influence of graphene nanoplatelets geometrical characteristics on the properties of polylactic acid composites, Diam. Relat. Mater. 126 (2022) 109092, doi:10.1016/J.DIAMOND.2022.109092.
- [307] A.A. Ansari, M. Kamil, Izod impact and hardness properties of 3D printed lightweight CF-reinforced PLA composites using design of experiment, Int. J. Light. Mater. Manuf. 5 (2022) 369–383, doi:10.1016/J.IJLMM.2022.04.006.
- [308] N. Vinoth Babu, N. Venkateshwaran, N. Rajini, S.O. Ismail, F. Mohammad, H.A. Al-Lohedan, S. Suchart, Influence of slicing parameters on surface quality and mechanical properties of 3D-printed CF/PLA composites fabricated by FDM technique, Mater. Technol. 37 (2022) 1008–1025, doi:10.1080/10667857.2021. 1915056.
- [309] E. García, P.J. Núñez, J.M. Chacón, M.A. Caminero, S. Kamarthi, Comparative study of geometric properties of unreinforced PLA and PLA-Graphene composite materials applied to additive manufacturing using FFF technology, Polym. Test. 91 (2020) 106860, doi:10.1016/J.POLYMERTESTING.2020.106860.
- [310] Q. Wei, J. Zhou, D. Sun, R. Yang, M. Li, Y. Wang, J. Zhang, Y. Wang, Atomic scale investigation on the structural and mechanical properties of carbon nanotubes reinforced polylactic acid composites, Macromol. Mater. Eng. 307 (2022) 2200092, doi:10.1002/MAME.202200092.
- [311] W. Ali, A. Mehboob, M.G. Han, S.H. Chang, Novel biodegradable hybrid composite of polylactic acid (PLA) matrix reinforced by bioactive glass (BG) fibres and magnesium (Mg) wires for orthopaedic application, Compos. Struct. 245 (2020) 112322, doi:10.1016/j.compstruct.2020.112322.
- [312] O.V. Bakina, L.Y. Ivanova, N.E. Toropkov, E.I. Senkina, M.I. Lerner, E.A. Glazkova, M.G. Krinitsyn, Core-Shell Fe-Fe3O4 nanoparticles for synthesizing PLA composites with low toxicity and high radiopacity, Phys. Mesomech. 25 (2022) 270–278, doi:10.1134/S1029959922030079/METRICS.
- [313] M. Basheer EP, S. Rajkumar, R. Karthikeyan, V.P. Pradeep, K. Marimuthu, Microstructural characterization and defects analysis of FDM based composite material (PLA-G-CF), Mater. Today Proc. 62 (2022) 2303–2309, doi:10.1016/J. MATPR.2022.04.095.
- [314] H. Rashidi, B. Najaf Oshani, I. Hejazi, J. Seyfi, Tuning crystallization and hydrolytic degradation behaviors of poly(lactic acid) by using silver phosphate, zinc oxide and their nano-hybrids, Polym. Technol. Mater. 59 (2020) 72–82, doi:10.1080/25740881.2019.1625382/SUPPL\_FILE/LPTE\_A\_ 1625382\_SM5061.DOCX.
- [315] T. Wang, C. Lin, D. Batalu, L. Zhang, J. Hu, W. Lu, In vitro study of the PLLA-Mg65Zn30Ca5 composites as potential biodegradable materials for bone implants, J. Magnes. Alloy. (2021), doi:10.1016/j.jma.2020.12.014.
- [316] D.A. Canales, F. Reyes, M. Saavedra, L. Peponi, A. Leonés, H. Palza, A.R. Boccaccini, A. Grünewald, P.A. Zapata, Electrospun fibers of poly (lactic acid) containing bioactive glass and magnesium oxide nanoparticles for bone tissue regeneration, Int. J. Biol. Macromol. 210 (2022) 324–336, doi:10.1016/J. IJBIOMAC.2022.05.047.
- [317] K. Chen, C. Liao, P. Li, X. Li, X. Li, Y. Zuo, A compatible interface of wheat straw/polylactic acid composites collaborative constructed using KH570–nano TiO2, J. Polym. Environ. 30 (2022) 2209–2221, doi:10.1007/ S10924-021-02359-0/METRICS.
- [318] P. Dadashi, A. Babaei, M.H. Abdolrasouli, Investigating the hydrolytic degradation of PLA/PCL/ZnO nanocomposites by using viscoelastic models, Polym. Eng. Sci. 62 (2022) 869–882, doi:10.1002/PEN.25893.
- [319] M. Eicher, D. Bajwa, J. Shojaeiarani, S. Bajwa, Biobased plasticizer and cellulose nanocrystals improve mechanical properties of polylactic acid composites, Ind. Crops Prod. 183 (2022) 114981, doi:10.1016/J.INDCROP.2022.114981.
- [320] N. Gama, A. Ferreira, D.V. Evtuguin, New poly(lactic acid) composites produced from coffee beverage wastes, J. Appl. Polym. Sci. 139 (2022) 51434, doi:10.1002/ APP.51434.

- [321] L. Goñi-Ciaurriz, I. Vélaz, Antibacterial and degradable properties of β-cyclodextrin-TiO2 cellulose acetate and polylactic acid bionanocomposites for food packaging, Int. J. Biol. Macromol. 216 (2022) 347–360, doi:10.1016/J. IIBIOMAC.2022.06.202.
- [322] A. Jafari, H. Mirzaei, M.A. Shafiei, V. Fakhri, A. Yazdanbakhsh, V. Pirouzfar, C.H. Su, S.R. Ghaffarian Anbaran, H.A. Khonakdar, Conductive poly(e-caprolactone)/polylactic acid scaffolds for tissue engineering applications: synergy effect of zirconium nanoparticles and polypyrrole, Polym. Adv. Technol. 33 (2022) 1427–1441, doi:10.1002/PAT.5611.
- [323] J. Kananathan, M. Samykano, K. Kadirgama, D. Ramasamy, M.M. Rahman, Comprehensive investigation and prediction model for mechanical properties of coconut wood-polylactic acid composites filaments for FDM 3D printing, Eur. J. Wood Wood Prod 801 (80) (2021) 75–100 (2021), doi:10.1007/ S00107-021-01768-1.
- [324] T. Kuang, M. Zhang, X. Lian, J. Zhang, T. Liu, S. Zhang, X. Peng, External flow-induced highly oriented and dense nanohybrid shish-kebabs: a strategy for achieving high performance in poly (lactic acid) composites, Compos. Commun. 29 (2022) 101042, doi:10.1016/J.COCO.2021.101042.
- [325] M. Arastouei, M. Khodaei, S.M. Atyabi, M.Jafari Nodoushan, The in-vitro biological properties of 3D printed poly lactic acid/akermanite composite porous scaffold for bone tissue engineering, Mater. Today Commun. 27 (2021) 102176, doi:10.1016/J.MTCOMM.2021.102176.
- [326] Y. Li, S. Qiu, J. Sun, Y. Ren, S. Wang, X. Wang, W. Wang, H. Li, B. Fei, X. Gu, S. Zhang, A new strategy to prepare fully bio-based poly(lactic acid) composite with high flame retardancy, UV resistance, and rapid degradation in soil, Chem. Eng. J. 428 (2022) 131979, doi:10.1016/J.CEJ.2021.131979.
- [327] C. Liao, K. Chen, P. Li, X. Li, Y. Zuo, Nano-TiO2 modified wheat straw/polylactic acid composites based on synergistic effect between interfacial bridging and heterogeneous nucleation, J. Polym. Environ. 30 (2022) 3021–3030, doi:10. 1007/S10924-022-02414-4/METRICS.
- [328] T.P.T. Nguyen, D.V. Nguyen, C.N.H. Thuc, Q.B. Bui, P. Perré, D.M. Nguyen, Valorization of starch nanoparticles on microstructural and physical properties of PLA-starch nanocomposites, J. Appl. Polym. Sci. 139 (2022) 51757, doi:10. 1002/APP.51757.
- [329] S. Qiu, J. Sun, Y. Li, T. Zhu, H. Li, X. Gu, B. Fei, S. Zhang, Life cycle design of fully bio-based poly(lactic acid) composites with high flame retardancy, UV resistance, and degradation capacity, J. Clean. Prod. 360 (2022) 132165, doi:10. 1016/J.JCLEPRO.2022.132165.
- [330] F.S. Shahar, M.T. Hameed Sultan, S.N.A. Safri, M. Jawaid, A.R. Abu Talib, A.A. Basri, A.U. Md Shah, Fatigue and impact properties of 3D printed PLA reinforced with kenaf particles, J. Mater. Res. Technol. 16 (2022) 461–470, doi:10.1016/J.JMRT.2021.12.023.
- [331] J. Zhao, G. Wang, J. Chai, E. Chang, S. Wang, A. Zhang, C.B. Park, Polylactic acid/UV-crosslinked in-situ ethylene-propylene-diene terpolymer nanofibril composites with outstanding mechanical and foaming performance, Chem. Eng. J. 447 (2022) 137509, doi:10.1016/J.CEJ.2022.137509.
- [332] H. Liu, R. Chen, X. Sun, F. Li, H. Shen, K. Wang, Q. Wang, Y. Li, D. Xie, J. Chen, Preparation and properties of PBAT/PLA composites modified by PVA and cellulose nanocrystals, J. Appl. Polym. Sci. 139 (2022) 51474, doi:10.1002/ APP.51474.
- [333] V.A. Yiga, M. Lubwama, P.W. Olupot, Thermal stability of unmodified and alkali-modified rice husks for flame retardant fiber-reinforced PLA composites, J. Therm. Anal. Calorim. (2022) 14720 147 (2022) 11049–11075, doi:10.1007/ S10973-022-11311-W.
- [334] W. Ali, A. Mehboob, M.G. Han, S.H. Chang, Effect of fluoride coating on degradation behaviour of unidirectional Mg/PLA biodegradable composite for load-bearing bone implant application, Compos. Part A Appl. Sci. Manuf. 124 (2019) 105464, doi:10.1016/j.compositesa.2019.05.032.
- [335] S. Shankar, L.F. Wang, J.W. Rhim, Incorporation of zinc oxide nanoparticles improved the mechanical, water vapor barrier, UV-light barrier, and antibacterial properties of PLA-based nanocomposite films, Mater. Sci. Eng. C. Mater. Biol. Appl. 93 (2018) 289–298, doi:10.1016/J.MSEC.2018.08.002.
- [336] Z. Liu, Y. Ge, L. Zhang, Y. Wang, C. Guo, K. Feng, S. Yang, Z. Zhai, Y. Chi, J. Zhao, F. Liu, The effect of induced membranes combined with enhanced bone marrow and 3D PLA-HA on repairing long bone defects in vivo, J. Tissue Eng. Regen. Med. 14 (2020) 1403–1414, doi:10.1002/TERM.3106.
- [337] C. Zhou, L. Liu, W. Wang, L. Zhao, M. Li, J. Li, B. Zhang, Y. Han, L. Wang, Z. Zhang, Fabrication and properties of PLA/nano-HA composite scaffolds with balanced mechanical properties and biological functions for bone tissue

- engineering application, Nanotechnol. Rev. 10 (2021) 1359–1373, doi:10.1515/NTREV-2021-0083/ASSET/GRAPHIC/J\_NTREV-2021-0083\_FIG\_010.JPG.
- [338] B. Zhang, L. Wang, P. Song, X. Pei, H. Sun, L. Wu, C. Zhou, K. Wang, Y. Fan, X. Zhang, 3D printed bone tissue regenerative PLA/HA scaffolds with comprehensive performance optimizations, Mater. Des. 201 (2021) 109490, doi:10.1016/I.MATDES.2021.109490.
- [339] H. Zhang, X. Mao, D. Zhao, W. Jiang, Z. Du, Q. Li, C. Jiang, D. Han, Three dimensional printed polylactic acid-hydroxyapatite composite scaffolds for prefabricating vascularized tissue engineered bone: an in vivo bioreactor model, Sci. Reports 71 (7) (2017) 1–13 (2017), doi:10.1038/s41598-017-14923-7.
- [340] I. Gendviliene, E. Simoliunas, M. Alksne, S. Dibart, E. Jasiuniene, V. Cicenas, R. Jacobs, V. Bukelskiene, V. Rutkunas, Effect of extracellular matrix and dental pulp stem cells on bone regeneration with 3D printed PLA/HA composite scaffolds, Eur. Cell. Mater. 41 (2021) 204–215, doi:10.22203/ECM.V041A15.
- [341] M.O.C. Maia-Pinto, A.C.B. Brochado, B.N. Teixeira, S.C. Sartoretto, M.J. Uzeda, A.T.N.N. Alves, G.G. Alves, M.D. Calasans-Maia, R.M.S.M. Thiré, Biomimetic Mineralization on 3D Printed PLA Scaffolds: on the response of human primary osteoblasts spheroids and in vivo implantation, Polymer 13 (2021) 74 Page13 (2020) 74, doi:10.3390/POLYM13010074.
- [342] C. Tu, J. Chen, C. Huang, Y. Xiao, X. Tang, H. Li, Y. Ma, J. Yan, W. Li, H. Wu, C. Liu, Effects of electromagnetic fields treatment on rat critical-sized calvarial defects with a 3D-printed composite scaffold, Stem Cell Res. Ther. 11 (2020), doi:10.1186/S13287-020-01954-7.
- [343] D.Y. Kwon, J.H. Park, S.H. Jang, J.Y. Park, J.W. Jang, B.H. Min, W.D. Kim, H.B. Lee, J. Lee, M.S. Kim, Bone regeneration by means of a three-dimensional printed scaffold in a rat cranial defect, J. Tissue Eng. Regen. Med. 12 (2018) 516–528, doi:10.1002/TERM.2532.
- [344] I. Tcacencu, N. Rodrigues, N. Alharbi, M. Benning, S. Toumpaniari, E. Mancuso, M. Marshall, O. Bretcanu, M. Birch, A. McCaskie, K. Dalgarno, Osseointegration of porous apatite-wollastonite and poly(lactic acid) composite structures created using 3D printing techniques, Mater. Sci. Eng. C 90 (2018) 1–7, doi:10.1016/J. MSEC.2018.04.022.
- [345] H. Zhang, X. Mao, Z. Du, W. Jiang, X. Han, D. Zhao, D. Han, Q. Li, Three dimensional printed macroporous polylactic acid/hydroxyapatite composite scaffolds for promoting bone formation in a critical-size rat calvarial defect model, Sci. Technol. Adv. Mater. 17 (2016) 136, doi:10.1080/14686996.2016. 1145532.
- [346] Z. Xu, B. Lin, C. Zhao, Y. Lu, T. Huang, Y. Chen, J. Li, R. Wu, W. Liu, J. Lin, Lanthanum doped octacalcium phosphate/polylactic acid scaffold fabricated by 3D printing for bone tissue engineering, J. Mater. Sci. Technol. 118 (2022) 229– 242, doi:10.1016/J.JMST.2021.09.069.
- [347] Z. Guo, Q. Zhang, X. Yang, Y. Fang, X. Qian, K. Sheng, Microcrystalline cellulose reinforced polylactic acid composites: comparison of fabrication method and cellulose content, J. Polym. Res. 30 (2023) 1–9, doi:10.1007/ 510965-023-03790-8/FIGURES/6.
- [348] Y.A. Alli, H. Anuar, M.R. Manshor, O.M. Bankole, N.A.A. Rahman, S.K. Olatunde, E.O. Omotola, P.O. Oladoye, O. Ejeromedoghene, J. Suhr, N.A. Sukindar, N.A.M. Nasir, Influence of nanocomposites in extrusion-based 3D printing: a review, Hybrid Adv 3 (2023) 100069, doi:10.1016/J.HYBADV.2023.100069.
- [349] S. Kumar, R. Dang, A. Manna, S. Sharma, S.P. Dwivedi, A. Kumar, C. Li, M. Abbas, Effect of chemically treated kenaf fiber on the mechanical, morphological, and microstructural characteristics of PLA-based sustainable bio-composites fabricated via direct injection molding route, Biomass Convers. Biorefinery 1 (2023) 1–17, doi:10.1007/S13399-023-04916-0/FIGURES/3.
- [350] M. Hussain, S.M. Khan, M. Shafiq, N. Abbas, Mechanical and degradation studies on the biodegradable composites of a polylactic acid matrix reinforced by Tricalcium Phosphate and ZnO nanoparticles for biomedical applications, JOM 75 (2023) 5379–5387, doi:10.1007/S11837-023-06086-W/TABLES/2.
- [351] S. Feng, F. Zhang, S. Ahmed, Y. Liu, Physico-mechanical and antibacterial properties of PLA/TiO2 composite materials synthesized via Electrospinning and solution casting processes, Coatings 9 (2019) 525 Page9 (2019) 525, doi:10.3390/ COATINGS9080525
- [352] R. Scaffaro, A. Maio, E.F. Gulino, G.D.M. Micale, PLA-based functionally graded laminates for tunable controlled release of carvacrol obtained by combining electrospinning with solvent casting, React. Funct. Polym. 148 (2020) 104490, doi:10.1016/J.REACTFUNCTPOLYM.2020.104490.
- [353] A. Tampau, C. González-Martínez, A. Chiralt, Polylactic acid-based materials encapsulating carvacrol obtained by solvent casting and electrospinning, J. Food Sci. 85 (2020) 1177–1185, doi:10.1111/1750-3841.15094.