Journal of Engineering in Industrial Research

Journal Homepage: http://www.jeires.com

Original Research

Poly (lactic acid) Bioactive Nanocomposites as Novel Food Packaging Materials

Ali Ahmad[a], Amin Sadrodin Reyazi[b]

[a] *Centre for Sustainable Infrastructure, Department of Civil and Construction Engineering, Milan University of Technology, Milan, Italy*

[b] *Centre for Sustainable Infrastructure, Department of Civil and Construction Engineering, Swinburne University of Technology, Melbourne, Australia*

ARTICLE INFO

Article history

Submitted: 03 July 2020
Revised: 17 October 2020
Accepted: 09 December 2020
Published: 29 December 2020
Manuscript ID: JEIRES-2012-1013

KEYWORDS

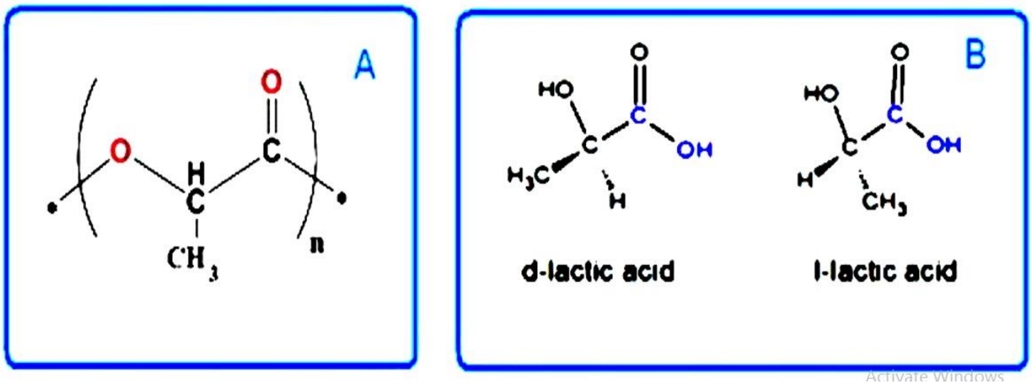
Bio nanocomposites
Rosin
Food packaging
Antioxidant
Vitamin E
Nontoxic

ABSTRACT

The progress of novel bioactive and antibacterial food packaging materials that prolong the shelf life of food is a significant purpose in food industry. Bioresource polymers like poly (lactic acid)(PLA) are superior compared with old style petroleum polymers like polypropylene. On the other hand, PLA is a natural based polymer that manufactured from sugar or starch in carbohydrate resources like rice, tapioca, molasses, wheat, sugar beet, corn, whey, wheat straw sugar cane, sweet potato, barley, corn stover and black wheat, so at recent years extruded PLA packages have been modified using phytochemical characterized preparations for extensive performs like cups, over wrap, blister packages and food containers. For improving renewable and degradable packaging materials, mixtures of PLA matrix with other fillers like anti-oxidants, proteins, vitamin E, rosin and various nanoparticles have also been explored in form of PLA nanocomposites applied as food packaging. This review paper aims at summarizing the researches on the new development of PLA nanocomposites for manufacturing active food packaging.

* Corresponding author: Ali Ahmad
✉ E-mail: Ali.1989@gmail.com

GRAPHICAL ABSTRACT



Introduction

Over the past few years, food packaging has advanced extremely owing to the different customer stresses. The inert character of packaging for logistic and selling purposes has progressed interested in a smart character for safety [1-3]. Since standard values of life have enhanced, numerous scientists have initiated to search the usage of natural bioactive resources in food packaging uses, for example polysaccharides (chitosan, alginates, celluloses, starch,) and natural hydrocolloids [4-6]. A lively purpose of food packaging has been established to cover a produce's shelf layer existence by means of reducing the include constituents that would release or absorb materials into or from the Packaged Food or the environment neighboring the food [1, 2, 5, 7]. Bioactive polymer composites are currently under the attention, because they can domain the quality of foods and prolong their shelf life. The greatest studied natural substances are those that are bioresourced, biobased and biodegradable, such as chitosan, poly(lactic acid), and starch[5, 8]. On the other hand Nanotechnology methods are being widened in food science [1]. Usage of nanotechnology in food packaging field has meaningfully addressed the food quality, food safety and food stability worries; Nanotechnology has been searched for controlled release of preservatives antimicrobial, spreading the food produce shelf life in the packaging. [9]. In most cases nanoparticles or nanostructure additives were incorporated with biodegradable green polymers to make nanocomposites for food packaging industrial uses, for example stated that antimicrobial silver montmorillonite nanoparticles prolonged the shelf life of fresh fruit salad, consequently incorporation of these appropriate nanostructure s with biosource polymers can prolong the shelf life of foods; [10, 11]. Hence these nanocomposites can be useful bioactive food packaging materials[12, 13]. Table 1 will demonstrate some nanocomposites applied in food packaging industry.

Table 1. Samples of presently accessible nanostructure food packaging in the shop [7, 14]

Nanocompsite type	Commercial product name:
Polyethylene+Ag nanoparticles	Fresh box nanosilver food container
Polypropylene+Ag nanoparticles	Baby dream silver nano noble product lines: nursing bottle, safe pacifier for new born and one touch mug cup
Polyethylene+Ag nanoparticles	Anson nano freshness keeping film; Anson nano freshness keeping storage bag, Anson nanosilver fresh containers
Silicon+Ag nanoparticles	Nanosilver food container
Polypropylene+Ag nanoparticles	Double handle nanosilver baby bottle

A Novel Biopolymer

Poly(Lactic Acid) [PLA] is a bioderived polymer (Figure 1). PLA is a model of biopolyesters namely biobased thermoplastic that also is ecocompatible. Such green polymers decrease the carbon cycle via repaying plant based carbon to the soil through biodegradation and otherwise decrease the environmental impact; henceforth, they decrease carbon dioxide emission throughout their life cycle. PLA is a biodegradable "green polymer" that decompose to provide H_2O, CO_2 and humus, the black material in soil; additionally, it has exclusive physical specifications which make it valuable in packaging industry [15-19].

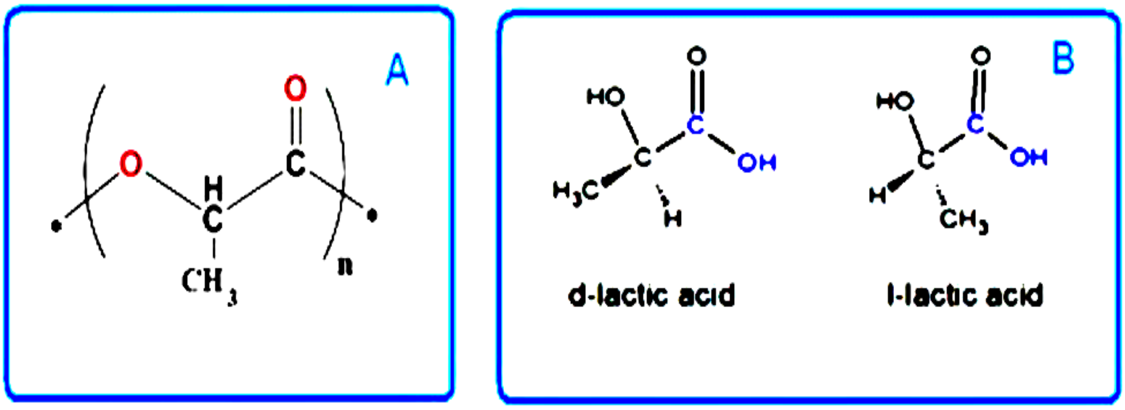


Figure 1. A) Chemical structure of PLA; **B)** Streoisomers of PLA

Ecology/cultivation

PLA have the chemical formulation of $[C_3H_6O_3]_n$ [20, 21] and it has been accepted with the food and drug administration (FDA). PLA manufactured from 100% renewable resources like corn, starch, sugar cane, wheat, sweet potato and rice [16, 22-24].

Biosynthesis

Lactic acid (2-hydroxypropionic acid, CH_3–CHOHCOOH) is the monomeric structural block of PLA. Lactic acid (a simple chiral molecule) is created commercially by means of a fermentation procedure from natural crops [11, 25-27]. Particular agronomic derivatives that are possible materials for lactic acid manufacture are corn starch, lignocellulose hemicellulose hydrolyzes, cotton seed hulls, jerusalem artichokes, corn cob, corn stalks, beet molasses, wheat bran, rye flour, sweet sorghum, sugarcane press mud, cassava, barley starch, cellulose, carrot processing waste, molasses spent wash, corn fiber hydrolyzes (Table 2)[28-31].

Table 2. Starchy sources and cellulosic materials applied for manufacturing the lactic acid [15, 32-35]

Bioresource	Microorganism
Wheat and Rice bran	Lactobacillus sp.
Corn cob	Rhizopus sp.MK 96 1196
Pretreated wood	Lactobacillus delbrueckii
Cellulose	Lactobacillus coryniformis ssp. torquens
Barley	Lactobacillus caseiNRRLB 441
Cassava bagasse	L. delbrueckii NCIM 2025, L casei
Wheat starch	Lactococcus lactis ssp. lactis ATCC 19435
Whole wheat	Lactococcus lactis ; Lactobacillus delbrueckii
Potato starch	Rhizopus oryzae, R. arrhizuso
Corn; rice, wheat starches	Lactobacillus amylovorous ATCC 33620
Corn starch	L. amylovorous NRRL B 4542

Poly (Lactic Acid) as a Food Packaging Matrix

PLA displays numerous benefits with respect to the petroleum based polymers typically applied for food packaging, those are:

Respectable transparency: This term frequently described as the transmission of visible light in the variety : 540–560 nm;

Degradation in biological environment: The biodegradation of PLA occurs in 2 chief phases, which are the hydrolytic degradation and enzymatic degradation;

Biocompatibility: PLA can degrade into nontoxic constituents;

Processability: The central conversion methods of PLA are based on melt processing. Profitable marks of PLA could classically be managed by means of a conservative twin screw extruder and melt viscosities of high molecular weight PLA are in the range of 500-1000 Pa s at shear rates of 10–50 s^{-1} [36-39].

Biological Activities of PLA Nanocomposites as Food Packaging Material

The contents of this article mainly concentrate on synthesis methods, physical and chemical properties, biological activity and safety assessments of different types of PLA nanocomposites in food packaging systems like yoghurt cups, lunch boxes , bottled water and bottled juices [2, 40, 41]. Several experiments examine the quality of PLA food packaging materials which will be discussed in next paragraphs:

Food simulants

As stated by council european directive 85/572/EEC, propagated with the european commission in 1985, laying down the tilt of food simulants which could be applied for testing migration the components of plastic materials 95% (v/v) aqueous ethanol and 3% (w/v) aqueous acetic acid were choice as food simulants [42-44].

Antioxidant activity

Food packaging materials should be Respectable anti-oxidants that efficiently slow the oxidization of particular foods, thus spreading their shelf life. RSA(radical scavenging activities) was expressed as the inhibition percentage and was calculated using the following formula [33, 37, 45, 46].

Antibacterial activity

An ideal food packaging material should be influential inhibitor of the growing and proliferation of numerous microorganisms, especially, gram negative bacteria, gram positive bacteria, and fungi. Antimicrobial food packaging can prevent the growing of degeneration microorganisms and therefore improve shelf life for food crops though preserving superiority and security. Since *escherichia coli* and *listeria monocytogenes* are characteristic spoilage organism collections in food products, the inhibition capability against these two bacteriological classes are verified for demonstration the antimicrobial activities [47-50].

Barrier properties to gases and vapors

Water vapor permeability **:** Water is a perceptible element in deterioration reactions and bacterial growth of food, consequently minimizing even avoid the moisture transferring between food and the nearby atmosphere converted significant. Oxygen permeability is reflected significant factor in the food packaging industry because of the character of oxygen in deteriorative responses and bacteriological growing [24, 51, 52].

Mechanical specifications

While a nanocomposite film is used for preserving food, it wants to preserve its integrity and resist outside stress, therefore the mechanical specifications are essential physical characteristics for the substance [25, 53, 54].

Migration content of nanoparticles in the food packaging materials

Migration process is the amount of matter that transferals from a substrate to a nearby solvent structure. In the example of packaging materials, the incorporation of extracts, like Ag nanoparticles or TiO_2 nanoparticles might be leaked to the food material. This is as manufacturers and users are concerned whether the leached spices can disturb the taste and shelf life of the packaged foodstuff. The migration of nanoparticles from films to 3% (w/v) aqueous acid food simulants solution is reflected as simulators of the releasing of nanoparticles to acidic food [55-57].

Opacity

Significantly, the exterior of food packaging affects the customers for purchasing them, so the transparency of food packaging materials is very important factor [13, 48, 58].

Biological and Phytochemical Assays of PLA Nanocomposites in Food Packaging Systems

This review references more than **90 articles** and summaries the up to date developments of PLA nanomaterials applied in the food packaging field, presenting a comprehensive review of various PLA nanocomposites and related technologies used to construct functional PLA food packaging nanosystems.

Tea polyphenol and PLA

Tea is the dried and prepared leaves of a shrub, Camellia sinensis, from which a somewhat bitter, aromatic beverage is prepared by infusion in hot water. **Teas polyphenol (TPs)** are a kind of phenolic compound exist in teas. These chemical compounds are antimicrobial and acting via avoiding microorganism attaching and with straight injuring cell structures [59]. These materials are great inhibitors for growth and proliferation of numerous microorganisms, especially, gram negative bacteria, gram positive bacteria, and Fungi. Furthermore, TPs are good antioxidants that efficiently hold up the oxidization of several foods, so spreading their shelf life. Discovering that green tea polyphenols have respectable anti-oxidant capabilities however reduced interfacial performances [60]. PLA TP nanofibers were effectively constructed via electrospinning method. Adding TP enhanced the anti-oxidant activities of the PLA nanofibers that measured with radical scavenging assay (PLA~ 2.5% ; PLA—TP (5:1) ~78%; PLA—TP (4:1) ~87%; PLA—TP (3:1) ~97%; PLA—TP (2:1) ~68%). Moreover, the PLA—TP 3:1 nanofibers displayed good anti—microbial activities against E. coli and S. aureus (92.26% ± 5.93% and 94.58% ± 6.53%, correspondingly). The releasing of TP from the PLA—TP nanofibers in 50% ethanol was quicker than that in the 95% ethanol fatty food simulants. This change could have been owing to the upper swelling degree of the PLA—TP nanofibers in 50% ethanol, the dispersion of the simulant to PLA film, and the relaxation of the PLA film, so that PLA—TP nanofibers have the prospective to be a bioactive material for food packaging [61].

Rosin and PLA

Rosin is the yellowish to amber, translucent, hard, brittle, fragmented resin left after distilling the oil of turpentine from the crude oleoresin of the pine; used chiefly in making varnishes, varnish and paint driers, printing inks, and for rubbing on the bows of such string instruments as the violin. **Rosin** displays nontoxic and antimicrobial physical characteristics that make it a prospective stabilizer for food packaging uses [62]. In a work in 2018**,** cellulose nanofibers (CNF) were improved by means of rosin and applied as reinforcement in PLA matrix (Figure 2). The PLA nanocomposites (PLA—rosin—CNF) were then covered by chitosan (CHT) to make a double layer nanocomposite (PLA—rosin—CNF—CHT) as a bioactive food packaging. Chitosan is a nontoxic, biodegradable, and biocompatible polymer technologically created from Chitin and the second greatest plentiful polysaccharide in environment. Chitosan has exposed antimicrobial properties against numerous food pathogens and has extraordinary film forming capability with oxygen permeability and moisture permeability. The antimicrobial examination displayed that the PLA—rosin—CNF—CHT nanocomposite presented outstanding antimicrobial activities against *E. coli* and *B. subtilis* that could be ascribed to the synergistic antimicrobial influence of chitosan and rosin [63] .

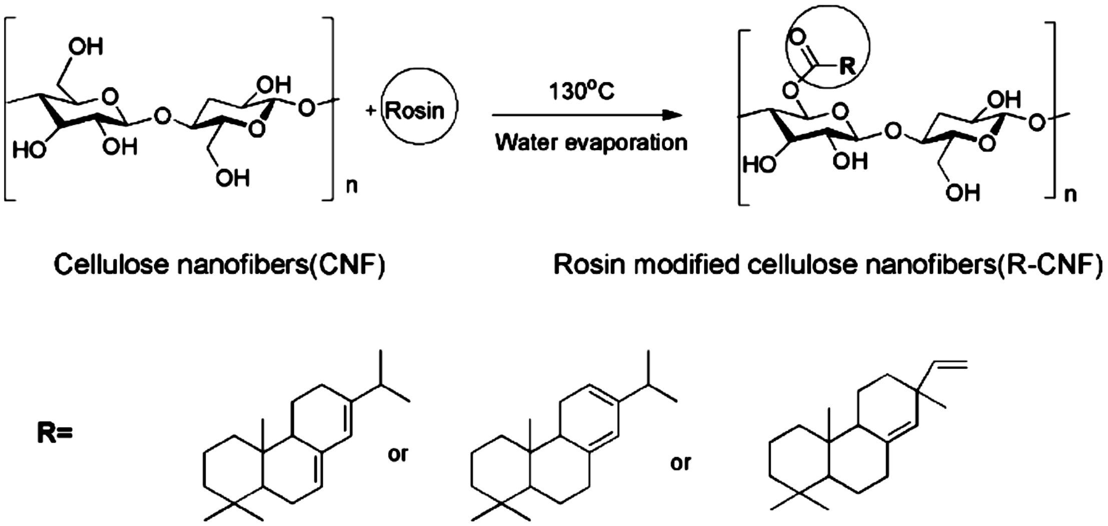


Figure 2. Production of rosin modified cellulose nanofibers [63]

Cellulose nanocrystals and PLA

PLA nanocomposites holding cellulose nanocrystals were manufactured via solvent casting method and converted to packaging used on mixture vegetables as food model. Bacteriological examination of mixture vegetables immunized with L. monocytogenes specified that PLA–CNC nanocomposites prompted a quasi-total inhibition of microbes in vegetables on day 14 and consequently proved a durable antimicrobial capability in-situ. The amount of total phenols releasing from bioactive nanocomposites was defined through folin ciocalteu's technique and outcomes displayed that total-phenols releasing improved from day 0 to day 14, equal to 16.6% on day 14. These outcomes demonstrated the durable antimicrobial capability of PLA–CNC nanocomposites as Food Packaging uses for vegetables [11].

Vitamin E and PLA

Vitamin E is a pale yellow viscous fluid, abundant in vegetable oils, whole grain cereals, butter, and eggs, and important as an antioxidant in the deactivation of free radicals and in maintenance of the body's cell membranes: deficiency is rare(Also called α-tocopherol). PLA nanofibers were mixed with silver nanoparticles (Ag—NPs) and vitamin E via electrospinning for food packaging uses. Nanofibers inhibited growth of *Escherichia coli, Listeria monocytogenes* and Salmonella typhymurium up to 100%. The antioxidant activity of nanofibers was estimated consistent with DPPH (2,2-diphenyl-1-picrylhydrazyl) technique and controlled as 94%. The outcomes of the examinations on fresh apple and apple juice specified that the PLA—Ag—Vitamin E nanofiber membrane vigorously decreased the polyphenol oxidase activity. PLA nanocomposites were made through "in situ" ring opening polymerization of lactide by means of a montmorillonite (Cloisite 15A: after surface modification with 3-Glycidoxy-Propyl-Trimethoxy-Silane). The results show that even very small concentrations (0.1% w/w) of nanoparticles significantly affect nanocomposites possessions , for instance melt crystallization temperatures improve with modified nanoparticles, which develop crystallization process [64].

Starch derivatives and PLA

Starch is a white, tasteless, solid carbohydrate, $(C_6H_{10}O_5)_n$, occurring in the form of minute granules in the seeds, tubers, and other parts of plants, and forming an important constituent of rice, corn, wheat, beans, potatoes, and many other vegetable foods. Yu *et al.* [8] formulated PLA nanocomposites with starch derivative (including plasticizing influence). The as-prepared Starch fluids showed liquid like performance and incorporated in PLA [8].

Mentha piperita , bunium percicum and PLA

Essential oils are multifaceted lipid oils naturally manufactured as secondary metabolites through plant substrates, like flowers, buds, seeds, leaves, wood, fruits, roots, twigs, and barks. As well as antibacterial activity, Essential oils furthermore own antifungal, antioxidant, antiviral, antimycotic, antitoxigenic, antiparasitic, antibiotic, and antiseptic specifications. Because of outstanding biological presentation, essential oils are the greatest applied extracts in the food industry. These biosource materials have been applied in food packaging for extending shelf life. In a different work in 2018, various amounts of mentha piperita essential oil, bunium percicum essential oil, and nanocellulose combined with PLA for producing antimicrobial nanocomposite films. The results demonstrated that mentha piperita and bunium percicum essential oils hold antimicrobial activities against *S. aureus, enterobacteriaceae, and pseudomonas* [65].

Konjac glucomannan and PLA

3 dimensional nanofibers cryogels (NFCs) have capacity for extensive uses in food fields; Yuan *et al* manufactured PLA—Konjac Glucomannan NFCs. Konjac glucomannan is accepted as a favored poly-saccharide owing to its non-toxicity , outstanding biodegradability and biocompatibility and respectable film materializing capacity. This new NFCs formulated by means of the combination of the mussel inspired protein polydopamine (PDA) using an electrospinning and freeze-shaping method. Furthermore, the strong intermolecular hydrogen bond interactions between konjac Glucomannan, PLA and PDA too provided great thermal stability and mechanically robust specifications for NFCs [66].

Mentha piperita L. , salvia officinalis L and PLA

The most vicious insect pests in stored food stuff crops are correspondingly coleoptera and lepidoptera that are extent in widespread variety of weathers and are found on every landform excepting antarctica. Numerous contaminations of stored food stuffs for example grains, nuts, and dried fruits are related to the multiethnic indian meal moth, plodia interpunctella (the food served and eaten especially at one of the customary, regular occasions for taking food during the day, as breakfast, lunch, or supper**)**. In 2017, electrospinning process was applied for incorporating different amounts of essential oils (Mentha piperita L. and Salvia officinalis L.) in PLA nanofibers. These essential oils can be released from the PLA nanofibers for elongated times, from numerous days to a number of weeks. Bioassays exposed those PLA nanofibers holding essential oils were more noxious than pure essential oils against tested larvae (The immature, wingless, feeding stage of an insect that undergoes complete metamorphosis). Consequently PLA nanofibers advanced the persistence of the oil. The outcomes demonstrated that S. officinalis has further fumigant(any volatile or volatilizable chemical compound used as a disinfectant or pesticide) toxicity and M. piperita had further perseverance to control the larvae of indian meal [67].

Candeia and PLA

Tonoli *et al.,* [68] assessed the influence of adding various amounts of candeia (eremanthus erythropappus) essential oil on the specifications of PLA nanostructure d materials. eremanthus erythropappus is a woodland type whose wood is commonly applied as barrier post, because of its great natural stability, and now is the raw material for construction of the essential oil, whose chief terpene is the alpha bisabolol, that deliberates antibacterial possessions that are necessary in the manufacturing of drugs.

Cinnamon and PLA

Cinnamon is the aromatic inner bark of any of several east indian trees belonging to the genus Cinnamonum, of the laurel family, esp. the bark of C. zeylanicum (Ceylon cinnamon), used as a spice, or that of C. loureirii (Saigon cinnamon), used in medicine as a cordial and carminative . Cyclodextrins (CD) are logically nontoxic cyclic (of or pertaining to a compound that contains a closed chain or ring of atoms (contrasted with acyclic)) oligosaccharides containing of α-1,4-linked glucopyranose units. There are three common CD kinds, α-CD, β-CD, and γ-CD that have 6, 7, and 8 glucopyranose components in the cyclic construction, correspondingly [69]. Cyclodextrins hold an exclusive truncated cone form molecular construction. Cyclodextrins hold an exceptional capability for procedure of inclusion complexes (IC) by various callers like antibacteria's and food additives; IC can improve permanence, solubility, bioavailability, functionality, and controlled sustained releasing of these caller molecules. Wen *et al.,* [69] mixed Cinnamon—ß-Cyclodextrin inclusion complex

(CEO—ß—CD—IC) within PLA nanofibers by means of electrospinning technique for food packaging uses. PLA—CEO—ß—CD nanocomposites presented superior antimicrobial activity (against *E. coli* and *S. aureus*) compared with PLA—CEO nanofilm, because the minimum inhibitory Concentration (MIC) of PLA—CEO—ß—CD nanocomposite against *E. coli* and *S. aureus* was about 1 mg/mL (Cinnamon essential oil : 11.35 μg/mL) and minimum bactericidal concentration (MBC) was around 7 mg/mL (Cinnamon essential oil : 79.45 μg/mL). The functionality of an antimicrobial nanocomposite in food packaging can be tested from the amount of microorganism growing. In best explorations a food is stated **Spoilt** while the amount of microorganisms on the food surface surpasses a total of 1×10^7 CFU/mL or g or cm^2. So, the PLA—CEO—ß—CD nanocomposite was used in the protection of flesh at 25 ˚C for evaluating its effectiveness in food antimicrobial packaging. The preliminary bacteria colonies of the flesh were 10^3–10^4 (CFU/g) in the first day, representative the fresh nature of the Flesh. The control (unpacked flesh) was rotten in the 4th day as the bacterial colonies were disproportionately more than 1×10^7 (CFU/g), and the shelf life of negative—control crowded with fresh keeping film was only three days. While, the Flesh packed with PLA—CEO—ß—CD nanocomposite putrefied on the eighth day, specifying that this antimicrobial nanocomposite can efficiently extend the shelf life of **Flesh**(the soft substance of an animal body, consisting of muscle and fat**)**, signifying it has possible use in bioactive food packaging [69].

Triclosan and PLA

Kayaci *et al.*, [70] prepared complexes including triclosan cyclodextrin (TR-CD/IC) and then combined into PLA nanofibers through electrospinning method**.**α-CD, β-CD and γ-CD were assayed for the forming of TR-CD/IC with a co—precipitation technique. The results demonstrated that PLA nanowebs incorporating TR-CD/IC can be applied as an active food packaging owing to excessive surface area and nanoporous organization in addition to effectual antibacterial activities.

Thymol and PLA

Innovative antioxidant PLA nanocomposites were made by way of adding in thymol, and modified montmorillonite (D43B) in 2 amounts . Thymol is a colorless, crystalline, slightly water-soluble solid, $C_{10}H_{14}O$, having a pungent, aromatic taste and odor, obtained from the oil distilled from thyme or prepared synthetically. Thermal stability was not meaningfully changed with the incorporating thymol, however the addition of D43B advanced mechanical properties, decreased the oxygen transmission rate. The quantity of thymol keeping in PLA constructions (that controlled with liquid/chromatography (HPLC—UV)) and the antioxidant activity (that controlled with the DPPH spectroscopic technique) is signifying that PLA—thymol/D43B nanocomposites can be present an auspicious antioxidant food packaging [71].

Soybean and PLLA

Soybean is a bushy old world plant, glycine max, of the legume family, grown in the U.S., chiefly for forage and soil improvement. Electrospinning method applied for fabricating PLLA—phosphorylated soybean protein isolate/zirconium Dioxide—Nisin Drug (PLLA—PSPI—ZrO_2—Nisin) nanofibrous membranes for Food Packaging. The outcomes showed that PLLA—PSPI—ZrO_2—Nisin nanofibrous membranes presented better antimicrobial activity against Staphylococcus aureus [72].

Cellulose nanocrystals and PLA

In a different research, PLA nanocomposites were manufactured for food packaging with cellulose nanocrystals (CNC), in addition **Silver** (Ag) nanomaterial was applied for positive controlling; also peptide structure that is recognized for antimicrobial property was incorporated to the PLA composite. All the samples were categorized by noteworthy inhibition of microbial growth in various periods [73].

Cellulose, SiO_2 and PLA

For Food Packaging, landfill biodegradation is desired; consequently in a novel examination in 2019, cellulose—SiO_2 nanocomposites were manufactured and melt-mixed with PLA via a twin screw extruder. Prominently, adding cellulose—SiO_2 at great amount overloading can approve landfill degradation of PLA through water-absorption capacity of cellulose [1].

Silver and PLA

High pressure denotes to a knowledge that forces liquid or gas to over 100 28 Mpa. As the maximum hopeful high pressure process in food processing and preservation technology, increasingly care has been salaried, and it has been extensively applied in the treating and protection of meat products, dairy products, fruits and vegetable products, aquatic products. Presently, the investigation hotspots of high pressure expertise chiefly emphasis on the high pressure sterilization influence of food microbes and food quality variations. **Fan** *et al.*, [74] explored the special effects of Ag nanoparticle amount(1%,5%, 10% and 20%), high pressure treating (100, 200, 300, and 400 MPa high pressure for 10, 20, and 30 min, respectively) on PLA—Ag nanocomposites. After high pressure treating the PLA samples soaked in isooctane food simulator at 40 °C for 49 days. **Isooctane** was applied as a food simulant to investigate the migration of Ag nanoparticles in PLA nanocomposites for fat food packaging. The food simulation liquid was applied for simulating the actual oily food packaging environs. The PLA nanocomposites and the simulated liquid were in dual sided contacting in relation to the standard factors of the European Food Safety Authority. The migration of Ag nanoparticles in the PLA nanocomposites improved with the incorporation of Ag nanoparticles, the pressure of high pressure process, and migration time. Furthermore, the incorporation of Ag nanoparticles may possibly advance the barrier specifications of the PLA nanocomposites. The outcomes specified that the migration quantity of Ag nanoparticles and presentation of the PLA—Ag nanocomposites were significantly marked with the migration time. The results demonstrated that while the PLA—Ag nanocomposites are applied for oily food packaging for a long time, its presentations will be ended, consequently the preservation time must not go above 35 days. This finding is serious to the expansion of nontoxic food packaging resources with outstanding concerts [74].

Zinc oxide and PLA

Shafiee nasab *et al.,* [75], investigated the influence of PLA films holding nanozinc oxide (ZnO:1, 3 and 5 wt%) on *Escherichia coli* and *Staphylococcus aureus* growth. The Diameter of the controller sample inhibition zone was about 0 cm, which specifies that PLA—ZnO films do not have antimicrobial activity ($P>0.05$), nevertheless wholly 3 PLA nanocomposite had inhibitory special influences, besides with increasing the amount of ZnO nanoparticles, expressively ($P<0.05$) improved the inhibitory outcomes [75].

ZnO, Silver and PLA

In 2017, PLA nanocomposite films were formulated for food packaging usage, with ZnO nanoparticles and Ag nanoparticles via Solvent—volatilizing method. PLA nanofilms presented respectable anti—microbial activity against E. coli, special the PLA—Ag+3 wt% ZnO and PLA—Ag +1 wt % ZnO [76].

Cu/Doped ZnO powder and PLA

Vasile *et al.,* [77] were organized PLA nanocomposites with Cu/Doped ZnO Powder functionalized by Ag nanoparticles using Melt—blending Processing system. Barrier antimicrobial specifications in detail to migration of Cu, Zn an Ag nanoparticles to food simulants were explained. The overall migration of all nanoparticles to three food simulants was under 10 $mg.dm^{-2}$. The results demonstrated that the best structure is PLA—ZnO:Cu—Ag 0.5, this nanocomposite proposing appropriate physical and thermal properties, respectable barrier specifications to ultraviolet light, water vapor, oxygen and carbon—dioxide, antibacterial properties and little migration quantity of nanoparticles to food simulants [77].

ZnO and PLA

In another rout, PLA nanocomposite films were attained by means of combining ZnO nanoparticles [untreated: ZnO (UT), 3-methacryloxyPropyltrimethoxysilane Treated: ZnO(ST)] in polymer through solvent casting technique for food preservation. The ZnO (ST) stopped the degradation of PLA at advanced temperature and developed the mechanical properties. Nanofilms particularly including ZnO (ST) were active against *Salmonella*

Typhimurium and *Listeria monocytogenes* bacteria [78].

Titanium dioxide and PLA

Titanium dioxide (TiO_2) is a white water insoluble powder that significantly used in the food industry. TiO_2 nanoparticles have respectable photocatalytic properties, wide ranging antibacterial and UV protection specifications. For food packaging uses, the photocatalytic activities (The acceleration or retardation of the reaction rate in chemical reactions by light) of the TiO_2 nanoparticles are primarily applied. Furthermore Ag nanoparticles are hopeful antimicrobial substrates, since Ag nanoparticles can enter bacteria and kill them via attachment to the cell membranes. Besides, the outsized surface area of Ag nanoparticles moreover has an operative inhibitory influence on the growing of the bacteria; consequently, they have been generally applied in the food packaging uses.

Silver, titanium dioxide and PLA

PLA—TiO_2 and PLA—TiO_2—Ag nanocomposites were manufactured via solvent volatilization process in 2017. TGA consequences display that adding nanoparticles meaningfully enhanced the thermal stability of this PLA food packaging. The main danger of shopper exposing to nanoparticles from food packaging is to be over possible migration of nanoparticles to food. The information about interactions among nanoparticles and humans through migration from food contact matters are necessary. The results demonstrate that Ag nanoparticles displaying alike migration as the TiO_2 ones. Nevertheless, the releasing of Ag nanoparticles was nearly a linear function throughout storage time. As the particle—size of Ag nanoparticles is around 10 nm, that is noteworthy lesser than the particle size of TiO_2 ones (about 100 nm), the Ag nanoparticles has a developed surface to volume ratio. Consequently, the migration ratio of the Ag nanoparticles was clearly greater than TiO_2 ones. (EU) No.10/2011 specifies that the whole amount of nanomaterial matters in barrier substrates in a food product should not surpass 1 mg.$^{kg-1}$, accordingly, the Ag and TiO_2 nanoparticles releasing of the PLA films were in the standard limitations [80] .

Carbon nanotubes and PLA

A different PLA nanocomposite with four armed star PLA immobilized on the outer surface of carbon nanotubes were prepared via ultrasonic procedure by means of noncovalent technique. This appropriate noncovalent process can be beneficial for the make of PLA—carbon nanotubes material without the damage of the inherent graphitic construction of the virgin carbon nanotubes for industrial food packaging.

Silica and PLA

Silica (silicon dioxide) is the dioxide form of silicon, SiO_2, occurring esp. as quartz sand, flint, and agate: used usually in the form of its prepared white powder chiefly in the manufacture of glass, water glass, ceramics, and abrasives. A novel nanocomposite including PLA matrix and Silica nanoparticles (SiO_2) as filler, were formulated by Pilic *et al.* [82] through solution casting system. The crystallinity of PLA is to some extent improved with adding 0.2 and 0.5 wt.% of nanofiller .

Chitin nanocrystals and PLA

Chitin is a nitrogen containing polysaccharide, related chemically to cellulose, which forms a semitransparent horny substance and is a principal constituent of the exoskeleton, or outer covering, of insects, crustaceans, and arachnids. In a different work, PLA nanocomposites prepared with melt compounding and film blowing. The incorporation of 1 wt.% Chitin nanocrystals improved the tear strength and the puncture strength thru 175% and 300% correspondingly.

Cloisite C30B and PLA

In an innovative exploration, PLA nanocomposite films [PLA with nanoclay and nanocellulose] were formulated by means of a commercial nanoclay (Cloisite C30B) and nanocellulose, in the arrangement of acetylated cellulose nanofibres (CNFs) or nanocrystalline cellulose. The combination of clay and nanocellulose clearly resulted in synergistic behavior in terms of the oxygen transmission rate over a decrease of up to 90% in OTR and a more decrease in the water vapor transmission Rate of equal to 76%. Moreover, the PLA nanocomposites displayed enhanced Thermo mechanical Resistance and developed crystallization kinetics while preserving great film Transparency.

Spherical nanocellulose formates and PLA

Spherical nanocellulose formates (SCNFs) were included to PLA for fabricating new nanocomposites. Adding of SCNFs meaningfully improved the crystallization rate, therefore led to obvious enhancements of the mechanical properties and thermal stability of the PLA. Additionally, the adding of SCNFs enhanced the barrier advantages and migration possessions of the PLA nanocomposite as food packaging.

Cellulose and PLA

Cellulose is an inert carbohydrate, $(C_6H_{10}O_5)_n$, the chief constituent of the cell walls of plants and of wood, cotton, hemp, paper. The influence of annealing process and cellulose nanofibers (surface treated SCN and surface untreated CN) on the properties of PLA was carefully considered by Frone *et al.,* for food packaging applications. Higher crystallinity was detected after annealing—process, 59% in place of 40% for PLA, 67% in place of 48% for CN—PLA nanocomposite and 57% in place of 39% for SCN—PLA nanocomposite, correspondingly.

Multiwalled carbon nanotube and PLA

Multiwalled carbon nanotube was modified with polymethyl—methacrylate (MWCNT—PMMA) via in-situ Solution Radical polymerization in the existence of 2,2′—Azobis (iso—butyronitrile) as an initiator. Two series of PLA nanocomposites with various MMA amounts and MWCNT—PMMA fillers were formulated through twin screw extruder and injection molding. The outcomes displayed that the mechanical specifications improved with increasing of MMA and MWCNT—PMMA.

Titanium oxide and PLA

PLA—TiO_2 nanocomposites were made using the melting procedure with titanium oxide~10 nm nanoparticles. TEM images demonstrated that TiO_2 nanoparticles evenly dispersed in the PLA polymer with a low amount of agglomeration.

Halloysite Nanotubes and PLA

In a different research, ZnO nanoparticles were deposited on the outside and internal sides of halloysite nanotubes (Hal) by means of solvo thermal process and these ZnO deposited hal (ZnO—Hal) were combined with the PLA polymer**.** Antimicrobial examinations exposed that PLA—ZnO—hal nanocomposite have favorable antimicrobial activities. The antimicrobial presentations of PLA nanocomposite films could be owing to the: **(A)** Generation of reactive oxygen species **(ROS)** (Like hydroxyl radicals, hydrogen peroxide and super oxide) as a product of photocatalytic activities (initiation with visible light and UV); **(B)** Creation of Zn^{2+} ions ; **(C)** Electrostatic interaction. PLA—ZnO nanocomposites displayed substandard mechanical specifications whereas ZnO—hal improved the mechanical properties. For example, the adding of 5% of ZnO—hal increased the tensile strength and elastic modulus through 30% and 65%, correspondingly. Finally it can say that PLA—ZnO—hal nanocomposites have a great capacity for using as a food packaging substance wherever strength is significant in excess of ductility (for instance solid food storage containers).

Graphene oxide and PLA

Graphene oxide overloaded by ZnO nanoparticles (GO–ZnO) was formulated and combined with PLA by means of a Solution Blending technique for food packaging field. Tensile examinations display that PLA—GO–ZnO nanocomposites have improved tensile strength compared with PLA film. Dynamic mechanical analysis results reveal a noteworthy improvement in storage modulus and glass transition temperature of the PLA nanocomposites.

Kaolinite silver and PLA

Novel nanocomposites were constructed from compatibilized PLA—poly(butylene adipate co terephthalate) blends for dried longan packaging. Kaolinite silver (AgKT) incorporated into PLA. Dried longan shelf exists as ultimately expected via experimental moisture sorption isotherm and thru Peleg model are nearly equal (~308 days) for the PLA nanocomposites. Moreover, silver releasing which offers long term antibacterial action is credited to Ag—KT's covered construction. The quantity of released silver ions moreover conforms to migration stages stated with the standard for food contact packages.

Cellulose nanocrystals and PLA

Fortunati *et al.,* applied cellulose nanocrystals (CNC) and surfactant modified cellulose nanocrystals (s—CNC) with Ag nanoparticles for fabricating PLA nanocomposites. The mixture of s—CNC and Ag nanoparticles improved the barrier effect of the nanofilms whereas the outcomes of migration for the PLA nanocomposites exposed that none of the samples surpassed the overall migration limit, as consequences were fine below 60 $mgkg^{-1}$ of simulator.

Nickel zinc and PLA

PLA—NiZn—LNR Magnetic nanocomposite was prepared via incorporation of Nickel Zinc (NiZn) Ferrite nanoparticles into PLA—matrix and liquid natural rubber (LNR) as compatibilizer, by means of thermo Haake internal mixer with melt blending technique. The best thermal conductivity of PLA—LNR nanocomposites attained by 4wt% NiZn; because of the operative mixture of NiZn—NiZn conductive nets.

Polyurethane and PLA

PLA—polyurethane—graphene oxide nanocomposite fibers hold durable antimicrobial characteristics against *S. aureus* and *E. coli*, owing to the outstanding antibacterial activity of graphene oxide membranes with great specific surface area. The adding of graphene oxide repressed the attaching and increasing of microbes on the composite outsides, signifying that such nanocomposite can be a respectable applicant substrate used in food packaging territory.

ZnO nanorod and PLA

In a different research, Pantani *et al.*, Manufactured PLA—ZnO nanocomposites as active food packaging material via melt compounding PLA and 0.5–3% ZnO rod like nanoparticles. The surface treatment of nanofiller via silanization (with triethoxy caprylylsilane) was essential for obtaining improved dispersion and limiting the reduction in molecular mass of PLA. In comparison to the virgin PLA the nanocomposites were active against both gram positive and gram negative bacteria; stronger antibacterial activity being demonstrated after 7 days passed time.

Silver, cellulose and PLA

In another research, PLA nanocomposites were formed using cellulose nanocrystals (CNCs) eventually surfactant modified (S—CNC) , Silver (Ag) nanoparticles in PLA by means of melt extrusion followed with a film formation route. The nanocomposite preserved the transparency assets of the PLA matrix.

Poly(butylene succinate) and PLA

Properties of PLA nanocomposites made by blending of PLA, poly(butylene succinate) (PBS), and nanoclay was explored. The average particle size of the dispersed PBS phase was decreased considerably from 7 µm to 30-40 nm with adding the clay in the mixture.

Glycidyl methacrylate and PLA

Scaffaro *et al.,* [48] manufactured PLA—PBAT (Poly butylene adipate co terephthalate) and its nanocomposites via melt blending method. Glycidyl methacrylate (GMA) has been applied as a reactive compatibilizer for development the interface between PLA and PBAT. SEM images expose better interfacial adhesion between the PLA-PBAT blend in existence of GMA and nanoclay.

Table 3, 4 and 5 will give a brief report of antibacterial properties, mechanical and physical specifications of PLA nanostructure s in food packaging applications.

Table 3. Antibacterial activities of PLA nanostructure food packaging materials

PLA nanocomposite	Bactria	Unit of antibactrail activity	Antibactrail activities According to the number of days												Ref.
			0 Hour	3 Hours	12 Hours	1 Day	2 Days	3 Days	4 Days	5 Days	6 Days	7 Days	8 Days	14 Days	
PLA	E.coli	Log_{10}(CFU/mL)	4.5	—	9.8	—	—	—	—	—	—	—	—	—	
PLA—ZnO	E.coli	Log_{10}(CFU/mL)	4.5	—	3.5	—	—	—	—	—	—	—	—	—	
PLA—Ag	E.coli	Log_{10}(CFU/mL)	4.5	—	3	—	—	—	—	—	—	—	—	—	[76]
PLA—Ag—1 % ZnO	E.coli	Log_{10}(CFU/mL)	4.5	—	2.4	—	—	—	—	—	—	—	—	—	
PLA—Ag—3 % ZnO	E.coli	Log_{10}(CFU/mL)	4.5	—	2	—	—	—	—	—	—	—	—	—	
PLA—CEO—ß—CD	E.coli	Log_{10}CFU/g	3.2	—	3.6	3.8	4	4.5	4.2	4.9	5	6	7.2	—	[69]
PLA	E.coli	Log_{10}CFU	6	—	11.4	11	—	—	—	—	—	—	—	—	
PLA—CHT	E.coli	Log_{10}CFU	6	—	9	9.2	—	—	—	—	—	—	—	—	
CNF—PLA—CHT	E.coli	Log_{10}CFU	6	—	8.5	8.6	—	—	—	—	—	—	—	—	
R/CNF—PLA—CHT	E.coli	Log_{10}CFU	6	—	8	8.3	—	—	—	—	—	—	—	—	
R/CNF—PLA	E.coli	Log_{10}CFU	6	—	9	9	—	—	—	—	—	—	—	—	
PLA	B. subitilis	Log_{10}CFU	6	—	10	9.5	—	—	—	—	—	—	—	—	[63]
PLA—CHT	B. subitilis	Log_{10}CFU	6	—	9	8.5	—	—	—	—	—	—	—	—	
CNF—PLA—CHT	B. subitilis	Log_{10}CFU	6	—	8.6	8.3	—	—	—	—	—	—	—	—	
R/CNF—PLA—CHT	B. subitilis	Log_{10}CFU	6	—	7.8	7.5	—	—	—	—	—	—	—	—	
R/CNF—PLA	B. subitilis	Log_{10}CFU	6	—	9	8.5	—	—	—	—	—	—	—	—	
PLA	E.coli	%	—	—	—	5	—	—	—	—	—	—	—	—	
PLA—TP 5:1	E.coli	%	—	—	—	70	—	—	—	—	—	—	—	—	
PLA—TP 4:1	E.coli	%	—	—	—	85	—	—	—	—	—	—	—	—	[61]
PLA—TP 3:1	E.coli	%	—	—	—	90	—	—	—	—	—	—	—	—	
PLA—TP 2:1	E.coli	%	—	—	—	80	—	—	—	—	—	—	—	—	
PLA	S.aureus	%	—	—	—	2.5	—	—	—	—	—	—	—	—	
PLA—TP 5:1	S.aureus	%	—	—	—	78	—	—	—	—	—	—	—	—	
PLA—TP 4:1	S.aureus	%	—	—	—	85	—	—	—	—	—	—	—	—	
PLA—TP 3:1	S.aureus	%	—	—	—	95	—	—	—	—	—	—	—	—	

PLA—TP 2:1	S.aureus	%	—	—	—	83	—	—	—	—	—	—	—	—	
PLA	Klebsiella - pneumoniae	CFU/mL	—	1.8E+08	—	4E+09	—	—	—	—	—	—	—	—	[73]
PLA—5% CNC	Klebsiella - pneumoniae	CFU/mL	—	1.8E+08	—	5E+09	—	—	—	—	—	—	—	—	
PLA—5% CNC—0.25 % Ag	Klebsiella - pneumoniae	CFU/mL	—	1.8E+08	—	4.5E+09	—	—	—	—	—	—	—	—	
PLA—5% CNC—0.75 % Ag	Klebsiella - pneumoniae	CFU/mL	—	1.8E+08	—	5E+09	—	—	—	—	—	—	—	—	
PLA—5% CNC/0.25 % Ppt	Klebsiella - pneumoniae	CFU/mL	—	0	—	2.5E+09	—	—	—	—	—	—	—	—	
PLA	E.coli	CFU/mL	—	1.20E+08	—	5.5E+09	—	—	—	—	—	—	—	—	
PLA/5% CNC	E.coli	CFU/mL	—	1.80E+08	—	4E+09	—	—	—	—	—	—	—	—	
PLA—5% CNC/0.25 % Ag	E.coli	CFU/mL	—	1.80E+08	—	4E+09	—	—	—	—	—	—	—	—	
PLA/5% CNC/0.75 % Ag	E.coli	CFU/mL	—	8.00E+07	—	2E+09	—	—	—	—	—	—	—	—	
PLA/5% CNC/1.25 % Ag	E.coli	CFU/mL	—	1.00E+00	—	0.3E+09	—	—	—	—	—	—	—	—	
PLA/5% CNC/0.25 % Ppt	E.coli	CFU/mL	—	1.00E+00	—	0.5E+09	—	—	—	—	—	—	—	—	
PLA	Listeria monocytogenes	CFU/mL	—	—	—	2.E + 08	3.E + 08	—	—	—	—	—	—	—	
PLA/5% CNC	Listeria monocytogenes	CFU/mL	—	—	—	3.E + 08	3.5E + 08	—	—	—	—	—	—	—	
PLA/5% CNC—0.25 % Ag	Listeria monocytogenes	CFU/mL	—	—	—	5.E + 07	2.5E + 08	—	—	—	—	—	—	—	
PLA/5% CNC/0.75 % Ag	Listeria monocytogenes	CFU/mL	—	—	—	3.E + 07	2E + 08	—	—	—	—	—	—	—	
PLA/5% (w/w) CNC/0.25 % Ppt	Listeria monocytogenes	CFU/mL	—	—	—	5.E + 07	2E + 08	—	—	—	—	—	—	—	
PLA/5% CNC/0.75 % Ppt	Listeria monocytogenes	CFU/mL	—	—	—	1.E + 00	8.E + 07	—	—	—	—	—	—	—	
PLA	Salmonella spp.	CFU/mL	—	2.00E + 08	—	7E + 09	—	—	—	—	—	—	—	—	
PLA/5% CNC	Salmonella spp.	CFU/mL	—	1.50E + 08	—	6E + 09	—	—	—	—	—	—	—	—	
PLA/5% CNC/0.25 % Ag	Salmonella spp.	CFU/mL	—	5.00E + 07	—	5E + 09	—	—	—	—	—	—	—	—	

PLA/5% CNC/0.75 % Ag	Salmonella spp.	CFU/mL	—	1.00E + 08— —	—	1E + 09	—	—	—	—			—	—	
PLA/5% CNC/1.25 % Ag	Salmonella spp.	CFU/mL	—	3.00E + 00		0.5E + 09	—	—	—	—	—	—	—		
PLA/5% CNC/0.25 % Ppt	Salmonella spp.	CFU/mL	—	1.00E + 08		4E + 09	—	—	—	—	—	—	—	—	
PLA/5% CNC/0.75 % Ppt	Salmonella spp.	CFU/mL	—	1.00E + 00		1E + 09	—	—	—	—	—	—	—	—	
PLA—5% CNC/1.25 % Ppt	Salmonella spp.	CFU/mL	—	2.00E + 00		0	—	—	—	—	—	—	—	—	
PLA	E.coli	Log_{10}CFU	6.8	—		6.5	—	—	—	—	—	6.5	—	—	
PLA/1% ZnO	E.coli	Log_{10}CFU	6.8	—	—	5.8	—	—	—	—	—	3.2	—	—	
PLA/2% ZnO	E.coli	Log_{10}CFU	6.8	—	—	5.8	—	—	—	—	—	4.3	—	—	
PLA/3% ZnO	E.coli	Log_{10}CFU	6.8	—	—	6	—	—	—	—	—	4.2	—	—	
PLA	S.aureus	Log_{10}CFU	7.2	—	—	7.1	—	—	—	—	—	5	—	—	
PLA/ 3% ZnO	S.aureus	Log_{10}CFU	7.1	—	—	6.8	—	—	—	—	—	2.1	—	—	
PLA/PEG/ 2.5% ZnO(UT)	Salmonella Typhimurium	Log_{10}(CFU/mL)	—	—	—	9.5	—	—	—	—	—	—	—	—	
PLA/PEG/ 5% ZnO(UT)	Salmonella Typhimurium	Log_{10}(CFU/mL)	—	—	—	9	—	—	—	—	—	—	—	—	
PLA/PEG/ 7.5 % ZnO(UT)	Salmonella Typhimurium	Log_{10}(CFU/mL)	—	—	—	8.5	—	—	—	—	—	—	—	—	
PLA/PEG/ 10 % ZnO(UT)	Salmonella Typhimurium	Log_{10}(CFU/mL)	—	—	—	8	—	—	—	—	—	—	—	—	
PLA/PEG/ 2.5 % ZnO(ST)	Salmonella Typhimurium	Log_{10}(CFU/mL)	—	—	—	9	—	—	—	—	—	—	—	—	
PLA/5 wt% ZnO(ST)	Salmonella Typhimurium	Log_{10}(CFU/mL)	—	—	—	8.5	—	—	—	—	—	—	—	—	[78] [78]
PLA/PEG/ 7.5 wt% ZnO(ST)	Salmonella Typhimurium	Log_{10}(CFU/mL)	—	—	—	8	—		—	—	—	—	—	—	
PLA/PEG/ 10 wt% ZnO(ST)	Salmonella Typhimurium	Log_{10}(CFU/mL)	—	—	—	6	—	—	—	—	—	—	—	—	
PLA/PEG/ 2.5 wt% ZnO(UT)	Listeria monocytogenes	Log_{10}(CFU/mL)	—	—	—	9	—	—	—	—	—	—	—	—	
PLA/PEG/ 5 wt% ZnO(UT)	Listeria monocytogenes	Log_{10}(CFU/mL)	—	—	—	8.3	—	—	—	—	—	—	—	—	
PLA/PEG/ 7.5 wt% ZnO(UT)	Listeria monocytogenes	Log_{10}(CFU/mL)	—	—	—	8	—	—	—	—	—	—	—	—	

PLA/PEG/ 10 wt% ZnO(UT)	Listeria monocytogenes	Log_{10}(CFU/mL)	—	—	—	8.1	—	—	—	—	—	—	—	—	
PLA/PEG/ 2.5 wt% ZnO(ST)	Listeria monocytogenes	Log_{10}(CFU/mL)	—	—	—	8.5	—	—	—	—	—	—	—	—	
PLA/PEG/ 5 wt% ZnO(ST)	Listeria monocytogenes	Log_{10}(CFU/mL)	—	—	—	8	—	—	—	—	—	—	—	—	
PLA/PEG/ 7.5 wt% ZnO(ST)	Listeria monocytogenes	Log_{10}(CFU/mL)	—	—	—	7.5	—	—	—	—	—	—	—	—	
PLA/PEG/ 10 wt% ZnO(ST)	Listeria monocytogenes	Log_{10}(CFU/mL)	—	—	—	6.5	—	—	—	—	—	—	—	—	
PLA	E.coli	Log_{10}(CFU/mL)	6.5	—	7	—	—	—	—	—	7.5	—	—	7.1	
PLA/2.5 % ZnO	E.coli	Log_{10}(CFU/mL)	6.5	—	4	—	—	—	—	—	2.7	—	—	2.3	
PLA/2.5 % ZnO—Hal	E.coli	Log_{10}(CFU/mL)	6.5	—	5	—	—	—	—	—	2.7	—	—	2	
PLA/5 % ZnO	E.coli	Log_{10}(CFU/mL)	6.5	—	4.5	—	—	—	—	—	2	—	—	1.8	
PLA/5 % ZnO—Hal	E.coli	Log_{10}(CFU/mL)	6.5	—	4.6	—	—	—	—	—	2.5	—	—	1.8	
PLA/7.5 % ZnO	E.coli	Log_{10}(CFU/mL)	6.5	—	2	—	—	—	—	—	0	—	—	0	
PLA/7.5 % ZnO—Hal	E.coli	Log_{10}(CFU/mL)	6.5	—	2.5	—	—	—	—	—	0	—	—	0	
PLA/10 % ZnO	E.coli	Log_{10}(CFU/mL)	6.5	—	0	—	—	—	—	—	0	—	—	0	
PLA/10 % ZnO—Hal	E.coli	Log_{10}(CFU/mL)	6.5	—	0	—	—	—	—	—	0	—	—	0	
PLA	S.aureus	Log_{10}(CFU/mL)	7.3	—	7.1	—	—	—	—	—	7.5	—	—	7.2	
PLA/ZnO	S.aureus	Log_{10}(CFU/mL)	7.5	—	5.5	—	—	—	—	—	2.8	—	—	2.3	[89]
PLA/2.5 % ZnO	S.aureus	Log_{10}(CFU/mL)	7.2	—	6.5	—	—	—	—	—	3	—	—	2	
PLA/2.5% ZnO—Hal	S.aureus	Log_{10}(CFU/mL)	7.8	—	3.8	—	—	—	—	—	2	—	—	1.8	
PLA/5 % ZnO	S.aureus	Log_{10}(CFU/mL)	7.5	—	6.5	—	—	—	—	—	2.5	—	—	1.8	
PLA/5 % ZnO—Hal	S.aureus	Log_{10}(CFU/mL)	7.5	—	~ 0	—	—	—	—	—	~ 0	—	—	~ 0	
PLA/7.5 % ZnO	S.aureus	Log_{10}(CFU/mL)	7.5	—	~ 0	—	—	—	—	—	~ 0	—	—	~ 0	
PLA/7.5% ZnO—Hal	S.aureus	Log_{10}(CFU/mL)	7.5	—	~ 0	—	—	—	—	—	~ 0	—	—	~ 0	
PLA/10 % ZnO	S.aureus	Log_{10}(CFU/mL)	7.5	—	~ 0	—	—	—	—	—	~ 0	—	—	~ 0	
PLA/10 % ZnO—Hal	S.aureus	Log_{10}(CFU/mL)	7.5	—	~ 0	—	—	—	—	—	~ 0	—	—	~ 0	
PLA	E.coli	Log_{10}(CFU/mL)	—	5	9	—	—	—	—	—	—	—	—	—	
PLA+ 1 % TiO_2	E.coli	Log_{10}(CFU/mL)	—	5	4.5	—	—	—	—	—	—	—	—	—	
PLA+5 % TiO_2	E.coli	Log_{10}(CFU/mL)	—	5	3.3	—	—	—	—	—	—	—	—	—	
PLA—1 % TiO_2—0.5 %A g	E.coli	Log_{10}(CFU/mL)	—	5	4	—	—	—	—	—	—	—	—	—	
PLA—5 % TiO_2 + 0.5 %A g	E.coli	Log_{10}(CFU/mL)	—	5	3	—	—	—	—	—	—	—	—	—	[80]
PLA	Listeria-monocytogenes.	Log_{10}(CFU/mL)	—	5	9.5	—	—	—	—	—	—	—	—	—	
PLA+ 1 %TiO_2	Listeria-monocytogenes.	Log_{10}(CFU/mL)	—	5	4.2	—	—	—	—	—	—	—	—	—	
PLA+5% TiO_2	Listeria-monocytogenes.	Log_{10}(CFU/mL)	—	5	3.8	—	—	—	—	—	—	—	—	—	

PLA+1% TiO_2 + 0.5 wt %A g	Listeria-monocyto genes.	Log_{10}(CFU/mL)	—	5	4	—	—	—	—	—	—	—	—	—	
PLA+5%Ti —0.5 %A g	Listeria-monocyto genes.	Log_{10}(CFU/mL)	—	5	3.5	—	—	—	—	—	—	—	—	—	
PLA	A. Niger	CFU/mL	—	—	—	—	—	—	—	—	—	2800000	—	—	[83]
PLA—Chitin	A. Niger	CFU/mL	—	—	—	—	—	—	—	—	—	800000	—	—	

Table 4. Mechanical specifications of PLA nanostructure food packaging materials

PLA nanocomposite	Elasticity modulus (EM)	Tensile strength (MPa)	Elongation of break (%)	Ref.
PLA	2900	55	0.036	[96]
PLA+1 wt% Ag	2100	45	0.031	
PLA	2892	46.6	7.6	
PLA+0.5% Bacterial Cellulose	3192	53.7	6.5	[97]
PLA+2% Bacterial Cellulose	3512	57.5	4.2	
PLA+5% Bacterial Cellulose	3678	55.3	2.1	
PLA	2700 (±200)	45 (±3)	9.3 (±2.4)	
PLA/1 wt% ZnO	2900 (±300)	44 (±5)	13.0 (±4.1)	
PLA/2 wt% ZnO	3000 (±150)	42 (±4)	7.1 (±1.5)	
PLA/3 wt% ZnO	2800 (±100)	39 (±2)	12.9 (±3.0)	
PLA	2528.20±223.54	36.15 ± 5.55	8.40 ± 0.11	
PLA/ZnO	2204.31±297.81	28.16 ± 2.69	12.22 ± 0.12	
PLA/Ag	2811.76±167.26	44.30 ±3.62	6.68 ± 0.10	[76]
PLA/Ag +1 wt % ZnO	2610.64±297.51	38.96 ± 8.19	7.74 ± 0.17	
PLA/Ag + 3 wt% ZnO	3118.79±333.39	47.78 ± 5.18	5.35 ± 0.06	
PLA	—	12.24 ± 4.5	57.28 ± 12.53	
PLA—TP 5:1	—	10.45±4.2	53.09 ± 11.75	
PLA—TP 4:1	—	9.28±3.6	51.71 ± 11.01	
PLA—TP 3:1	—	9.28 ± 3.6	50.36 ± 10.88	
PLA—TP 2:1	—	4.86 ± 2.3	24.72 ± 4.34	
PLA/PEG/2.5 wt% ZnO(UT)	—	26.1 ± 3.1	33.2 ± 2.3	
PLA/PEG/5 wt% ZnO(UT)	—	23.8 ± 2.6	30.9 ± 2.7	
PLA/PEG/7.5 wt% ZnO(UT)	—	21.4 ± 3.4	29.1 ± 3.0	[78]
PLA/PEG/10 wt% ZnO(UT)	—	22.6 ± 2.8	30.7 ± 2.1	
PLA/PEG/2.5 wt% ZnO(ST)	—	29.2 ± 2.6	34.2 ± 1.9	
PLA/5 wt% ZnO(ST)	—	33.9 ± 2.1	33.4 ± 3.1	
PLA/PEG/7.5 wt% ZnO(ST)	—	33.1 ± 3.4	32.2 ± 2.5	
PLA/PEG/10 wt% ZnO(ST)	—	34.6 ± 3.9	32.9 ± 2.7	
PLA	0.9 GPa	37	6.2%	
PLA/2.5 % ZnO	1.2 GPa	35	3.2%	
PLA/2.5 % ZnO—Hal	1.5 GPa	48	3.1%	
PLA/5 % ZnO	1.3 GPa	37	2.7%	[89]
PLA/5 % ZnO—Hal	1.6 GPa	49	2.6%	
PLA/7.5 % ZnO	1.1 GPa	31	3.1%	
PLA/7.5 % ZnO—Hal	1.5 GPa	41	3%	
PLA/10 % ZnO	1.2 GPa	33	3%	
PLA/10 % ZnO—Hal	1.45 GPa	42	3.1%	
PLA/1% CNC	2645	17.5	4.48%	
PLA/1% CNC + 0.25% Ag	2659	18.7	4.99	
PLA/1% CNC + 0.75% Ag	2681	17.4	4.98	[73]
PLA/1% CNC + 1.25% Ag	2687	17.6	5.12	
PLA/2.5% CNC	2700	22.1	4.55	
PLA/2.5% CNC + 0.25% Ag	2711	21.5	4.79	
PLA/2.5% CNC + 0.75% Ag	2696	22.9	5.38	
PLA/2.5% CNC + 1.25% Ag	2721	22.3	4.20	

PLA/5% CNC	2864	23.1	5.10	
PLA/5% CNC + 0.25% Ag	2899	23.3	4.86	
PLA/5% CNC + 0.75% Ag	2985	22.7	5.04	
PLA/5% CNC + 1.25% Ag	2945	24.1	5.14	
PLA/1% CNC	2395	19.5	6.02	
PLA/1% CNC + 0.25% Ppt	2559	18.7	5.94	
PLA/1% CNC + 0.75% Ppt	2349	19.4	6.90	
PLA/1% CNC + 1.25% Ppt	2499	17.1	6.92	
PLA/2.5% CNC	2511	22.4	6.59	
PLA/2.5% CNC + 0.25% Ppt	2601	20.1	6.71	
PLA/2.5% CNC + 0.75% Ppt	2649	19.3	6.45	
PLA/2.5% CNC + 1.25% Ppt	2224	15.3	9.20	
PLA/5% CNC	2844	22.1	5.46	
PLA/5% CNC + 0.25% Ppt	2817	22.3	5.09	
PLA/5% CNC + 0.75% Ppt	2605	18	5.99	
PLA/1% CNC + 1.25% Ppt	2536	16.1	6.31	
PLA	—	—	48	
PLA + 0.2 wt% SiO_2	—	—	63	
PLA + 0.5 wt% SiO_2	—	—	60	
PLA + 1 wt% SiO_2	—	—	55	[82]
PLA + 2 wt% SiO_2	—	—	58	
PLA + 3 wt% SiO_2	—	—	48	
PLA + 5 wt% SiO_2	—	—	45	
PLA	3027.53±176.41	15.16 ± 8.89	40.36 ± 1.74	
PLA+ 1 wt % TiO_2	3381.82 ± 26.57	11.43 ± 1.51	42.54 ± 2.38	
PLA+5 wt % TiO_2	3754.56±132.15	5.73 ± 1.17	46.94 ± 3.64	[80]
PLA+1 wt % TiO_2 +0.5 wt %Ag	3375.24±131.50	11.66 ± 3.17	49.57 ± 3.84	
PLA+5 wt % TiO_2 +0.5 wt %Ag	3554.96±64.43	9.69 ± 3.58	60.05 ± 7.05	
PLA	2400 ± 100	43.0±5.0	90±10	
PLA + 1 wt % Ag	2520±50	22.0±3.0	11±2	
PLA + 5 wt % CNC	2930±20	28.3±0.6	36±1	
PLA + 5 wt % CNC +1 wt % Ag	2700±100	29.0±2.0	27±5	
PLA + 5 wt % S—CNC	4400±200	46.1±3.0	18±1	
PLA + 5 wt % S—CNC +1%Ag	3000±200	40.8±3.0	60±5	
PLA	1079 ± 93	—	11.5 ± 0.40	
PLA + 1 wt % TiO_2	1057 ± 58	—	8.4 ± 0.18	
PLA + 3 wt % TiO_2	1298 ± 92	—	5.5 ± 0.14	[88]
PLA + 5 wt % TiO_2	1634 ± 43	—	5.8 ± 0.11	
PLA + 8 wt % TiO_2	1447 ± 59	—	7.4 ± 0.18	
PLA	0.8 ± 0.2(GPa)	33 ± 2	282 ± 15	[83]
PLA+ ChNCs	0.7 ± 0.1(GPa)	35 ± 3	281 ± 12	
PLA—PBAT(72:25)—% GMA	1314.23	22.75	6.6	
PLA—PBAT(70:25)—5%GMA	1746.4	30.52	6.5	
PLA—PBAT(67:25)—5%C20A+3%GMA	1841.40	19.36	2.8	
PLA—PBAT(65:25)—5%C20A+5wt%GMA	2106.66	26.55	2.4	
PLA/LNR + 1wt% NiZn	6181.34	36.85	4.83	
PLA/LNR + 2wt% NiZn	6227.25	37.71	4.82	
PLA/LNR + 3wt% NiZn	6253.45	39.62	2.54	
PLA/LNR + 4wt% NiZn	6553.41	42.79	2.74	[1]
PLA/LNR + 5wt% NiZn	5926.14	37.71	1.63	
PLA	4048±17	69.28±0.18	2.14±0.10	
PLA + O.5 wt % (ZnO : Cu—Ag)	2934±161	45.32±7.53	2.78±0.23	
PLA + 1 wt % (ZnO : Cu—Ag)	3058±72	48.39±5.35	2.67±0.52	[77]
PLA + 1.5 wt % (ZnO : Cu—Ag)	3010±107	47.28±2.75	2.61±0.27	

Table 5. Physical aspects of PLA nanostructure as food packaging materials

Sample	Opacity (%)	Gas permeability(cm3・mm/m2・day・atm)					Water absorption (%)	Ref.
		Water vapor ($\times10^{-14}$kgm/m^{2}sPa)	CO_2	O_2	N_2	Air		
PLA	—	0.21±0.01	—	2.23±0.22	—	—	—	
PLA+1 wt% ZnO	—	0.25±0.01	—	1.83±0.03	—	—	—	[75]
PLA+3 wt% ZnO	—	0.25±0.01	—	1.81±0.24	—	—	—	
PLA+5 wt% ZnO	—	0.24±0.02	—	1.84±0.06	—	—	—	
PLA	—	—	8.1	2	0.8	1.05	—	
PLA+0.2 wt% SiO_2	—	—	5.3	1	0.05	0.2	—	
PLA+0.5 wt% SiO_2	—	—	4.3	0.95	0.07	0.2	—	
PLA+1 wt% SiO_2	—	—	4	0.9	0.1	0.2	—	[82]
PLA+2 wt% SiO_2	—	—	4.7	0.95	0.07	0.2	—	
PLA+3 wt% SiO_2	—	—	6	1.2	0.05	0.2	—	
PLA+5 wt% SiO_2	—	—	6.2	1.25	0.03	0.2	—	
PLA	1.5	1.7	—	—	—	—	—	
PLA/ZnO	6.1	2.4	—	—	—	—	—	
PLA/Ag	0.6	1.75	—	—	—	—	—	
PLA/Ag +1 wt % ZnO	1.5	1.8	—	—	—	—	—	[76]
PLA/Ag + 3 wt% ZnO	7.8	2.4	—	—	—	—	—	
PLA	15	8.26×10^{-7}	—	—	—	—		
PLA+ 0.5 wt% ZnO	18	—	—	—	—	—	—	
PLA+1 wt% ZnO	20	9.81×10^{-7}	—	—	—	—	—	
PLA+2 wt% ZnO	21	—	—	—	—	—	—	
PLA+3 wt% ZnO	25	6.43×10^{-7}	—	—	—	—	—	
PLLA—ZrO_2	—	—	—	—	—	—	13%	
PLLA—ZrO_2 +5 wt% PSPI	—	—	—	—	—	—	20%	[72]
PLLA/ZrO_2+10 wt% PSPI	—	—	—	—	—	—	30%	
PLLA/ZrO_2+15 wt% PSPI	—	—	—	—	—	—	45%	
PLLA/ZrO_2+20 wt% PSPI	—	—	—	—	—	—	65%	
PLA	1.60 ± 0.03	2.5	—	—	—	—	—	
PLA+ 1 wt % TiO_2	3.43 ± 0.05	2.1	—	—	—	—	—	
PLA+5 wt % TiO_2	6.58 ± 0.08	1.7	—	—	—	—	—	
PLA+1 wt % TiO_2 + 0.5 wt %A g	4.57± 0.04	2.2	—	—	—	—	—	[80]
PLA+5 wt % TiO_2 + 0.5 wt %A g	7.31 ± 0.04	1.6	—	—	—	—	—	
PLA—PBS	—	6.5	—	21	—	—	—	
PLA—PBS : 80/20 + 1 wt % clay	—	9	—	17	—	—	—	
PLA—PBS:80/20+3 wt % clay	—	8.5	—	16	—	—	—	[1]

PLA—PBS:80/20+5 wt % clay	—	7.8	—	15	—	—	—	
PLA—PBS:80/20 +7 wt % clay	—	7.8	—	15.5	—	—	—	
PLA—PBS:80/20+10 wt % clay	—	8	—	15.5	—	—	—	
PLA+O.5 wt % (ZnO :Cu—Ag)	—	11.35	230	97	—	—	—	
PLA + 1 wt % (ZnO:Cu—Ag)	—	18.72	Invalid test	Invalid test	—	—	—	[77]
PLA+1.5 wt %(ZnO :Cu—Ag)	—	15.60	Invalid test	Invalid test	—	—	—	

Conclusion

Biobased polymers are considered as outstanding candidates to develop "environmentally friendly" materials that would also reduce our fuel dependency. Among them, PLA has been recognized to play a major role to achieve such an objective. Although PLA is a versatile polymer with outstanding physical and biological properties, it still requires further improvements in order to fully achieve its potential. The review has comprehensively presented methods of modifying PLA focusing on packaging applications. Special attention has been given to provide a detail recount of the inherent mechanisms responsible for the improved properties, in terms of the deformation mechanisms in the case of toughen PLA for food packaging applications.

References:

[1]. N. Bumbudsanpharoke, S. Ko, *Journal of Nanomaterials*, 2019.

[2]. M. Das Purkayastha, A.K. Manhar, Nanotechnological Applications in Food Packaging, Sensors and Bioactive Delivery Systems. In: Ranjan S, Dasgupta N, Lichtfouse E, eds. Nanoscience in Food and Agriculture 2. Cham: Springer International Publishing; 2016:59-128.

[3]. S. Allahvaisi, K.T. Jahromi, S. Imani, M. Khanjani, *Journal of Plant Protection Research*, 2017, 57(1):72–80

[4]. C Sharma, R Dhiman, N Rokana, H. Panwar, *Nanotechnology and Food Packaging*, 2017, 8

[5]. H. Ebrahimi BA, H. Bodaghi, G. Davarynejad, H. Haratizadeh, A. Conte. *Journal of Food Processing and Preservation*, 2018, 42 (2)

[6]. B. Tyler, D. Gullotti, A. Mangraviti, T. Utsuki, H. Brem, *Advanced Drug Delivery Reviews*, 2016, 107:163-175

[7]. S. Pirsa IKS, S. Khodayvandi. *Polymers for Advanced Technologies*, 2018, 29(11): 2750–2758

[8]. Q. Yu, Y. Li, L. Han, X. Yin, J. Xu, Y. Zhou, D. Chen, Z. Du, L. Wang, Y. Tan, *Composites Science and Technology*, 2019, 169: 76–85

[9]. A. Brandelli, Brum, L. F. W., and dos Santos, J. H. Z. *Environ Chem Lett*, 2017, 15: 193–204

[10]. T.J. Gutierrez, A. G. Ponce, A.V. Alvarez, *Mater Chem Phys*, 2017, 194: 283–292

[11]. S. Salmieri, F. Islam, R.A. Khan, F.M. Hossain, H.M.M. Ibrahim, C. Miao, W.Y. Hamad, M. Lacroix, *Cellulose*, 2014, 21(6): 4271-4285

[12]. F. Vilarinho MA, G.G. Buonocore, M. Stanzione, M.F. Vaz, A. Sanches Silva, *European Polymer Journal*, 2018, 98: 362–367

[13]. K. Lertphirun, K. Srikulkit, *International Journal of Polymer Science*, 2019

[14]. N. Bumbudsanpharoke, S. Ko, *Journal of Food Science*, 2015, 80(5)

[15]. M. Nofar, D. Sacligil, P.J. Carreau, M.R. Kamal, M-C. Heuzey. *International Journal of Biological Macromolecules*, 2019, 125:307-360

[16]. R. Scaffaro, F. Lopresti, D'ArrigoM, Marino A, A N, *Appl Microbiol Biotechnol*, 2018, 102: 4171–4181

[17]. F. Sadat Fattahi. *Nanomed Res J*, 2019, 4(3): 130-140

[18]. F. Fattahi, H. Izadan, A. Khoddami, 4th International Color and Coatings Congress (ICCC 2011) November 22-24, 2011 Tehran–Iran, 2011.

[19]. F. Fattahi, H. Izadan, A. Khoddami, *Prog Color Colorants Coat*, 2012, 5: 15-22

[20]. E. Castro-Aguirre RA, S. Selke, M. Rubino,T. Marsh, . *Impact of nanoclays on the biodegradation of poly (lactic acid) nanocomposites. 10*, 2018, 10(2)

[21]. Akbari A, Majumder M, Tehrani A. Polylactic Acid (PLA) Carbon Nanotube Nanocomposites. In: Kar KK, Pandey JK, Rana S, eds. Handbook of Polymer Nanocomposites. Processing, Performance and Application: Volume B: Carbon Nanotube Based Polymer Composites. Berlin, Heidelberg: Springer Berlin Heidelberg; 2015:283-297.

[22]. M. Mohiti-Asli, S. Saha, S.V. Murphy, H. Gracz, B. Pourdeyhimi, A. Alqtish, E. Loboa, Ibuprofen loaded PLA nanofibrous scaffolds increase proliferation of human skin cells in vitro and promote healing of full thickness incision wounds in vivo; 2015

[23]. G. Birhanu, S. Tanha, H. Akbari Javar, E. Seyedjafari, A. Zandi-Karimi, B. Kiani Dehkordi, *Pharmaceutical Development and Technology*, 2018:1-10

[24]. C.J. Su, M.G. Tu, L.J. Wei, T.T. Hsu, C.T. Kao, T.H. Chen, T.H. Huang, *Materials*, 2017, 10

[25]. J.L. Markley, R. Brüschweiler, A.S. Edison, H.R. Eghbalnia, R. Powers, D. Raftery, D.S. Wishart, *Current Opinion in Biotechnology*, 2017, 43: 34-40

[26]. Zhe Wang, Z Pan, Jigen Wang, R. Zhao, *Journal of Nanomaterials*, 2016

[27]. F-s. Fattahi, A. Khoddami, O. Avinc, *Pamukkale Univ Muh Bilim Derg*, In-press

[28]. F.S. Fattahi, A. Khoddami, H. Izadian, *Journal of Textile Science and Technology*, 2015, 5(1):11-17

[29]. Fattahi FS, A Khoddami, H. Izadan, *Journal of Apparel and Textile Science and Technology*, 2017, (2):19-26

[30]. Iulian, D Popescu, A Zapciu, A Antoniac, F Miculescu, H. Moldovan, *Materials*, 2019, 12 (719)

[31]. F.S. Fattahi, *LAP LAMBERT Academic publishing*, 2019, 978-620-0-49758-1

[32]. T. Yang, W. Zhou, P. Ma, *Polymers*, 2019, 11(65)

[33. F. Rezaei, A. Nikiforov, R. Morent, N. De Geyter, *Scientific Reports*, 2018, 8(1):2241

[34]. F-s. Fattahi, A. Khoddami, O. Avinc, *Journal Of Textiles And Polymers*, 2019, 7(2): 47-64

[35]. F.S. Fattahi, *Nanomed Res J*, 2019, 4(3):141-156

[36]. Q.B. Lin, H. Li, H.N. Zhong, Q. Zhao, D.H. Xiao, Z.W. Wang. *Food Addit Contam Part A*, 2014, 31: 1284–1290

[37]. R. Scaffaro, F. Lopresti, M. D'Arrigo, A. Marino, A. Nostro, *Applied Microbiology and Biotechnology*, 2018, 102:4171–4181

[38]. M. Mohiti-Asli, S. Saha, S.V. Murphy, H. Gracz, B. Pourdeyhimi, A. Atala, E.G. Loboa, *J Biomed Mater Res Part B.*, 2017, 105:327–339

[39]. F.S. Fattahi, A. Khoddami, O. Avinc, *Journal of Nanostructures*, In-press

[40]. J. Lv, X. Yin, Q. Zeng, W. Dong, H. Liu, L. Zhu. *J Polym Res*, 2017, 24 (60)

[41]. N. Herrera, H. Roch, A.M. Salaberria, A.M. Pino-Orellana, J. Labidi, C.M.S Fernandes, D. Radic, A. Leiva, K. Oksman, *Materials and Design*, 2016, 92: 846–852

[42]. H. Norazlina, Y. Kamal, *Polymer Bulletin*, 2015, 72(4): 931-961

[43]. A. Doustgani, E. Ahmadi, *Journal of Industrial Textiles*, 2016, 45(4):626-634

[44]. J. Li, Z. Song, L. Gao, H. Shan, *Polymer Bulletin*, 2016, 73(8): 2121-2128

[45]. W. Li, C. Zhang, H. Chi, L. Li, T. Lan, P. Han, H. Chen, Y. Qin, *Molecules*, 2017, 22

[46]. M. Andima, G. Costabile, L. Isert, A.J. Ndakala, S. Derese, O.M. Merkel. *Pharmaceutics*, 2018, 10(232)

[47]. A. Magiera, J.B. Markowski, E. Menaszek, J. Pilch, S. Blazewicz, *Journal of Nanomaterials*, 2017

[48]. R. Scaffaro, F. Lopresti, A. Marino, A. Nostro, *Applied Microbiology and Biotechnology*, 2018, 102:7739–7756

[49]. G. Birhanu, S. Tanha, H. Akbari Javar, E. Seyedjafari, A Zandi-Karimi, B.K. Dehkordi, *Pharmaceutical Development and Technology*, 2018

[50]. H. Tsuji, *Advanced Drug Delivery Reviews*, 2016, 107:97-135

[51]. k. Tipachan, *key engineering materials*, 2016, 718: 10-14

[52]. Y. Huang, T. Wang, X. Zhao, X. Wang, L. Zhou, Y. Yang, F. Liao, Y. Ju, *Journal of Chemical Technology & Biotechnology*, 2015, 90 (9): 1677-1684

[53]. E. Calzoni, A. Cesaretti, A. Polchi, A.D. Michele, B. Tancini, C. Emiliani, *J Funct Biomater.*, 2019, 10(4)

[54]. S. Handali, E. Moghimipour, M. Rezaei, S. Saremy, F.A. Dorkoosh, *Int J Biol Macromol.*, 2019, 124: 1299–1311

[55]. F. Lu, H. Yu, C. Yan, J. Yao, *RSC Advances*, 2016, 6(51): 46008-46018

[56]. J. Trifol, D. Plackett, C. Sillard, P. Szabo, J. Bras, A.E. Daugaard, *Polymer International*, 2016, 65(8): 988-995

[57]. A.N. Frone, D.M. Panaitescu, I. Chiulan, C.A. Nicolae, Z. Vuluga, C. Vitelaru, C.M. Damian, *Journal of Materials Science*, 2016, 51(21): 9771-9791

[58]. X. Wu, J. Qiu, W. Zhang, L. Zang, E. Sakai, P. Liu, *Polymer Composites*, 2016, 37(2): 503-511

[59]. L. Zhang, S. Li, Y. Dong, H. Zhi, W. Zong. *LWT-Food Sci Technol*, 2016, 70: 155–161

[60]. K.R. Koech, F.N. Wachira, R.M. Ngure, J.K. Wanyoko, C.C. Bii, S.M. Karori, L.C. Kerio, *Afr Crop Sci J*, 2014, 22: 837–846

[61]. Y. Liu, X. Liang, S. Wang, W. Qin, Q. Zhang. *Polymers*, 2018, 10(561)

[62]. Z. Shi, Q. Yang, S. Kuga, Y. Matsumoto , *Journal of Agricultural and Food Chemistry*, 2015, 63:6113–6119

[63]. S. Girdthep, P. Worajittiphon, R. Molloy, S. Lumyong, T. Leejarkpai, W. Punyodom. *Polymer*, 2014, 55(26): 6776–6788

[65]. F. Talebi, A. Misaghi, A. Khanjari, A. Kamkar, H. Gandomi, M. Rezaeigolestani, *LWT-Food Sci Technol*, 2018, 96:482–490

[66].

[67]. S. Allahvaisi, K.T. Jahromi, S. Imani , M. Khanjani, *Journal of Plant Protection Research*, 2017, 57 (1):72-80

[68]. E. Fortunati, M. Peltzer, I. Armentano, A. Jiménez, J.M. Kenny. *Journal of Food Engineering*, 2013, 118 (1): 117-124

[69]. P. Wen, D-H. Zhu, K. Feng, F-J. Liu, W-Y. Lou, N. Li, M-H. Zong, H. Wua, *Food Chemistry*, 2016,196: 996–1004

[70]. R. Pantani, G. Gorrasi, G. Vigliotta, M. Murariu, P. Dubois, *European Polymer Journal*, 2013, 49: 3471–3482

[71]. M. Ramos, A. Jiménez, M. Peltzer, M.C. Garrigós, *Food Chemistry*, 2014, 162:149-155

[72]. S. Jiang, H. Wang, C. Chu, X. Ma, M. Sun, S. Jiang, *International Journal of Biological Macromolecules*, 2015, 72: 502–509

[73]. M. George, W.Z. Shen, Z. Qi, A. Bhatnagar, *Journal of Polymer and Textile Engineering*, 2017, 4(3):8-24

[74]. M. Mucha, S. Bialas, H. Kaczmarek, *J APPL POLYM SCI*, 2014

[75]. M.S. Nasab, M. Tabari. *Nanomed Res J*, 2018, 3(3): 125-132

[76]. Z. Chu, T. Zhao, L. Li, J. Fan, Y. Qin, *Materials*, 2017, 10:659

[77]. C. Fonseca, A. Ochoa, M.T. Ulloa, E. Alvarez, D. Canales, P.A. Zapat, *Materials Science and Engineering C*, 2015, 57: 314–320

[78]. Y. A.Arfata, J. Ahmeda, A. Al Hazzab, H. Jacoba, A. Joseph, *International Journal of Biological Macromolecules*, 2017, 101: 1041–1050

How to Cite This Manuscript: Ali Ahmad, Amin Sadrodin Reyazi. Poly (lactic acid) Bioactive Nanocomposites as Novel Food Packaging Materials. *Journal of Engineering in Industrial Research*, (*J. Eng. Indu. Res.*), 2020, 1(2), 134-160. DOI: 10.22034/jeires.2020.263117.1013