

## Review Paper

# The Development of Green Polylactic Acid (PLA) Composites for Wastewater Treatment – A Review

Andriy Anta KACARIBU<sup>1)</sup>, Yuliani AISYAH<sup>2)</sup>, Febriani FEBRIANI<sup>3)</sup>,  
Darwin DARWIN<sup>4)</sup>\*

<sup>1)</sup> *Doctoral Program of Agricultural Science, Postgraduate School*

<sup>2)</sup> *Department of Food Product Technology, Faculty of Agriculture*

<sup>3)</sup> *Department of Chemistry, Faculty of Mathematics and Natural Sciences*

<sup>4)</sup> *Department of Agricultural Engineering, Faculty of Agriculture*

*Universitas Syiah Kuala*

Banda Aceh 23111, Aceh, Indonesia

\*Corresponding Author e-mail: darwin\_ae@usk.ac.id

Polylactic acid (PLA) is a biodegradable polyester derived from renewable resources, recognized for its environmental sustainability and versatile properties. Its applications span the biomedical, textile, and packaging industries and, more recently, wastewater treatment. This review explores recent advancements in the use of PLA and its composites for wastewater treatment, emphasizing their effectiveness, modification techniques to enhance performance, and future research directions. A thorough literature review was conducted, covering the past decade studies, and, including research articles, reviews, and case studies on PLA's application in wastewater treatment and comparative performance against other adsorbents. Although PLA's natural adsorption capacity is limited, it has demonstrated significant potential for removing contaminants such as heavy metals, organic dyes, and other organic pollutants. Various modifications, including surface chemical changes, physical blending with nanomaterials, and more, have notably improved its adsorption performance. Modified PLA composites thus present a viable and sustainable solution for wastewater treatment. Continued research is essential to further optimize these modifications, explore novel composite materials, develop scalable technologies, and assess long-term environmental impacts. This review offers a critical synthesis of current knowledge on PLA-based materials in wastewater treatment, aiming to inform and guide future research in sustainable water purification technologies.

**Keywords:** polylactic acid (PLA); wastewater treatment; adsorbents; adsorption; PLA composites; environmental sustainability.



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## 1. INTRODUCTION

Polylactic acid (PLA) is an aliphatic polyester (polylactide) recognized for its environmentally friendly and biodegradable properties [1, 2]. Derived from re-

newable resources such as agricultural waste, it is an eco-friendly alternative for substituting conventional synthetic polymers [3, 4]. PLA is produced through the polycondensation of lactic acid and/or via ring-opening polymerization (ROP) of lactide [5, 6]. In recent decades, PLA has gained significant attention across a wide range of industrial applications, including automotive, sports [7, 8], biomedical [9, 10], textile [11, 12], and packaging sectors [13, 14]. This is due to its excellent mechanical and thermal properties [15, 16]. One of the most recent and promising applications of PLA is in wastewater treatment, a highly relevant area given the increased industrial wastewater production requiring effective and sustainable treatment methods [17, 18].

The industry sector plays a crucial role as an active contributor to the international markets of numerous developing countries, and significantly contributes to the generation of wastewater [19]. Industrial wastewater contains hazardous contaminants such as chemicals, dissolved and suspended particles, organic matter, nutrients, and pathogenic microorganisms [20, 21]. Inadequate wastewater treatment can cause severe environmental pollution and threaten human health [22, 23]. Therefore, developing effective, economical, and environmentally friendly wastewater treatment technologies is crucial to address these challenges [24].

Numerous wastewater treatment methods have been reported by researchers, including flocculation, coagulation/flocculation [25], electrocoagulation [26], electrocoagulation integrated membrane ultrafiltration [27], integrated oxidation processes [28], electrocoagulation-assisted adsorption (ECA) [29, 30], chemical precipitation, electrochemical precipitation [31, 32], evaporation [33, 34], chemical oxidation/advanced oxidation processes (AOPs) [35, 36], anaerobic digestion [37, 38], and adsorption [39, 40]. Among these, adsorption is currently one of the most widely used methods in wastewater treatment [41, 42]. Adsorption can be carried out using various types of adsorbents, such as chitosan [43, 44], cellulose [45, 46], starch [47, 48], nanoparticle [49, 50], and PLA [51, 52].

PLA has emerged as a promising material (adsorbent) for wastewater treatment due to its unique advantages over other biodegradable polymers like starch, chitosan, and cellulose. Although starch-based adsorbents are biodegradable and cost-effective, they suffer from low viscosity, instability, poor adsorption capacity for heavy metals, and limited thermal stability, which restricts their effectiveness in removing organic dyes, hazardous materials, or toxic ions [53]. Despite its high adsorption capacity, chitosan dissolves in acidic solutions, tends to form gels, and is prone to rapid agglomeration, reducing its efficiency in some adsorption procedures; it also has poor mechanical strength [54, 55]. Meanwhile, cellulose faces challenges in optimizing regeneration processes, enhancing chemical stability under extreme conditions, and improving scalability and cost-effectiveness for industrial applications [56]. In contrast, PLA offers supe-

rior mechanical strength and controlled biodegradability [57]. PLA is highly scalable and commercially available [58], benefiting from widespread industrial applications and advancements in production technologies. Moreover, its compatibility with nanomaterials facilitates the creation of functional composites with enhanced adsorption efficiency and additional properties such as photocatalytic or antibacterial activity [59–62]. Combining PLA with nanomaterials, along with their versatility and potential for functionalization, positions PLA composites as a cutting-edge solution for current and future wastewater treatment applications, highlighting their significant potential in achieving sustainable and efficient pollution control.

To enhance adsorption capacity, PLA can be modified through various methods such as surface chemical modification, composite formation with nanomaterials, and electrospinning techniques, among others [63]. These methods significantly improve PLA's adsorption capacity, making it more effective in removing contaminants from wastewater.

Surface chemical modification of PLA involves introducing new functional groups that interact more effectively with contaminants [64]. For example, modifying PLA with nano-clay or activated carbon has significantly improved its adsorption capacity. This technique combines PLA's mechanical strength with the high adsorption potential of these nanomaterials, resulting in better removal of methylene blue (MB) [65]. Additionally, modification with strong bases or organic solvents can produce new hydrophobic and hydrophilic functional groups on PLA's surface, enhancing MB adsorption by approximately 75% [63]. Electrospinning is also reported as another technique used to modify PLA nanofibers. For instance, PLA modified with poly(ethylene glycol)–poly(propylene glycol)–poly(ethylene glycol) (PEG-PPG-PEG) and silica produces nanofibrous adsorbents with higher adsorption capacities for copper ions ( $\text{Cu}^{2+}$ ) compared to pure PLA [66].

Another study demonstrated an innovative approach to fabricating floating adsorbent beads using a one-pot process (OP bead) combining PLA and maleic anhydride (MAH)-modified cellulose derived from waste lemongrass leaves (LGL). This process involved modifying cellulose microfibers without grinding and forming sorbent beads through phase separation, utilizing unreacted MAH and dimethylacetamide (DMAc) as pore formers and solvents. Compared to conventional methods, the OP beads exhibited improved thermal stability, enhanced surface porosity, and superior MB adsorption with an 86.19 mg/g capacity. The adsorption behavior followed the pseudo-second-order (PSO) kinetic model and Langmuir isotherm model, with the beads retaining 88% of their adsorption efficiency after five cycles. Additionally, the beads selectively adsorbed cationic dyes such as MB while repelling anionic dyes such as methyl orange (MO) [67].

Previous studies also reported that PLA is versatile for direct modification and functions effectively as a filler or functional additive. The incorporation of nano-sized PLA onto graphene oxide (GO) through a facile synthesis approach, for the first time, demonstrated improved adsorption performance for MB and tetracycline (TC) from aqueous solution. The modified GO-PLA composite exhibited optimal adsorption conditions at an adsorbent dose of 0.5 g/L, contact time of 120 minutes, pH 4, at a temperature of 318 K. The PSO kinetic model indicated that chemisorption governed the adsorption mechanism, while the intraparticle diffusion model revealed contributions from both surface adsorption and intraparticle diffusion. The Langmuir isotherm model best described the adsorption behavior, with maximum monolayer uptake capacities of 332.5 mg/g and 223.7 mg/g for MB and TC, respectively. These values reflect significant improvements of approximately 70% and 110% for MB and TC, respectively, compared to unmodified GO. The enhancement is attributed to the nano-sized PLA, which introduced additional functional groups and increased the composite's surface area [68]. By exploring the use of PLA composites in wastewater treatment, more effective and economical methods can be developed to address existing aquatic environmental issues.

However, many aspects still require further investigation to optimize the use of PLA in wastewater treatment. One of the main challenges is the production and modification costs of PLA. Effective modification processes often involve expensive materials and technologies, which can limit the industrial-scale application of PLA [66]. This literature review aims to examine and analyze the use of PLA composites in wastewater treatment, focusing on modification methods, their effectiveness as adsorbents, and the prospects of PLA in this field. Thus, this review seeks to provide a solid foundation for further research and the development of more effective and environmentally friendly wastewater treatment technologies.

## 2. LACTIC ACID AND POLYLACTIC ACID

Lactic acid (LA), also known as 2-hydroxy propanoic acid has the chemical formula  $\text{CH}_3\text{-CH(OH)-COOH}$  and is an organic acid obtained through biotechnological fermentation [69]. LA was first isolated and described by Karl Wilhelm Scheele (1742–1786) in 1780 from sour milk and was mass-produced by C.E. Avery in Littleton, MA, USA, in 1881 [70]. Generally, LA is chiral, existing as two optical isomers: L-(+)-lactic acid (LLA) and D-(–)-lactic acid (DLA) [71], as shown in Fig. 1. Both isomers can be applied in various sectors, including the food industry (as an emulsifier, preservative, buffering agent, and acidulant) [29, 30], textile, pharmaceuticals, chemical industry, and packaging [72, 73]. Re-

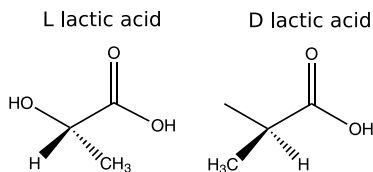


FIG. 1. Optical isomers of lactic acid [77].

cently, LA has been widely used as a precursor for producing PLA polymers for wastewater treatment [74], as summarized in Table 1.

TABLE 1. Applications of LA in various fields.

PLA	Chemical industry	Industries	Medicine	Food technology
<ul style="list-style-type: none"> <li>• Packaging</li> <li>• Film composite</li> <li>• Adsorbent</li> </ul>	<ul style="list-style-type: none"> <li>• Ethyl lactate</li> <li>• Acrylic acid</li> <li>• Propanoic acid</li> <li>• Propylene glycol</li> </ul>	<ul style="list-style-type: none"> <li>• Textile</li> <li>• Detergent</li> <li>• Paper</li> <li>• Cosmetics</li> </ul>	<ul style="list-style-type: none"> <li>• Dialysis and parenteral solution</li> <li>• Lactate mineral formulation</li> </ul>	<ul style="list-style-type: none"> <li>• Emulsifier</li> <li>• Acidulant</li> <li>• Preservatives</li> <li>• Buffering agent</li> </ul>

Numerous microorganisms can be used as inocula to produce LA from various substrates through fermentation, including yeast, algae, and bacteria. Among these, lactic acid bacteria (LAB) are the most commonly used genera for LA fermentation [76, 77]. LAB are Gram-positive bacteria widely employed in the bioproduct industry. They belong to the order *Lactobacillales*, which includes genera such as *Lactobacillus*, *Lactococcus*, *Aerococcus*, *Enterococcus*, *Leuconostoc*, *Streptococcus*, *Pediococcus*, *Vagococcus*, *Carnobacterium*, *Tetragenococcus*, *Weissella*, and *Oenococcus* [78, 79]. LABs are naturally found in diverse environments and can be isolated from human mucosal surfaces, meat, milk, animal microbiomes, and plants [80, 81]. Therefore, LABs are considered highly suitable as fermentation inoculum for LA production.

Two common methods for LA production are chemical synthesis and microbial fermentation, as illustrated in Fig. 2. Chemical synthesis of LA is associated with high costs and significant environmental pollution. This method involves the initial formation of acetonitrile (2-hydroxy propionitrile) through a reaction between acetaldehyde and hydrogen cyanide under high temperature and pressure conditions. The resulting acetonitrile undergoes purification via distillation and then hydrolyzed using concentrated sulfuric acid ( $\text{H}_2\text{SO}_4$ ) or hydrochloric acid ( $\text{HCl}$ ) to yield racemic LA as the primary product. However, this method relies on petroleum-derived raw materials, which are expensive, non-renewable, and pose significant environmental concerns [82].

In contrast, microbial fermentation produces pure lactic acid (either D- or L-LA), depending on the type of microorganism used. This process utilizes en-

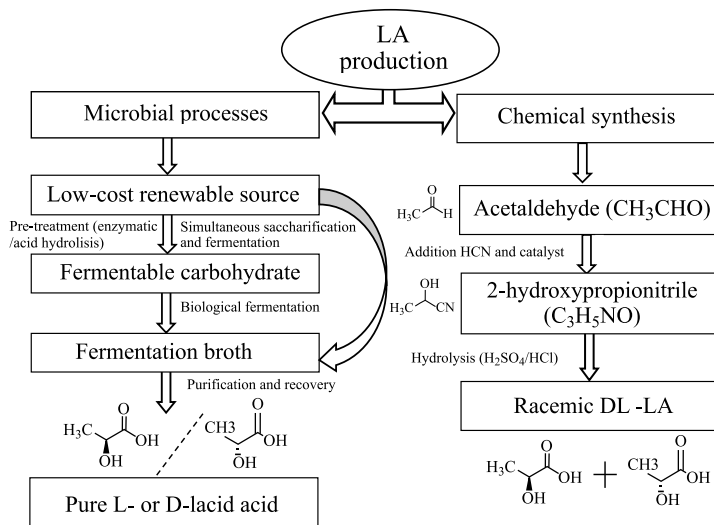


FIG. 2. LA production scheme [77].

environmentally friendly, carbohydrate-rich raw materials that are inexpensive, abundant, and do not compete with food sector [77, 83, 84]. Microbial fermentation accounts for the majority of global LA production, making it one of the most favorable methods for LA production [85, 86]. However, LA obtained from fermentation broth cannot be directly used as a precursor for polylactic acid synthesis without further processing. The LA must be separated and purified from the fermentation broth [74, 87]. This purification process is complex and expensive, necessitating the need for more cost-effective and simpler methods to reduce production expenses. Numerous techniques for the separation and purification of lactic acid from fermentation broth have been reported by researchers, including precipitation, liquid-liquid extraction, membrane separation, adsorption, and distillation [77].

The increasing demand for composite materials has attracted significant attention from researchers, primarily due to their superior properties across diverse applications [88, 89]. One key advantage of composite materials over conventional materials is their high strength-to-weight ratio [90]. Traditionally, synthetic composites are made from synthetic polymers derived from petroleum, which are less favored due to their environmental drawbacks, including non-biodegradability and unsustainability. Furthermore, the depletion of petroleum resources caused by extensive consumption has intensified the urgency for alternatives. PLA-based composites are a promising solution to replace non-biodegradable and unsustainable composites [75, 91, 92].

PLA is synthesized from the monomer LA, first discovered by the Swedish chemist Scheele in 1780 [93]. The polymerization of lactic acid into PLA oc-

curs through four stages: LA dehydration, polycondensation, depolymerization, and ring-opening polymerization (ROP) of lactide [74], as illustrated in Fig. 3. The chemical structure of PLA can be altered by adjusting the ration of D or L-LA monomers during polymerization, using appropriate catalysts and specific reaction conditions. Although pure PLA generally has a semi-crystalline structure, it can be produced with amorphous or crystalline characteristics [94]. Thus, through monomer component manipulation, PLA can be obtained in semi-crystalline, amorphous, or crystalline forms, providing versatility in its use [95].

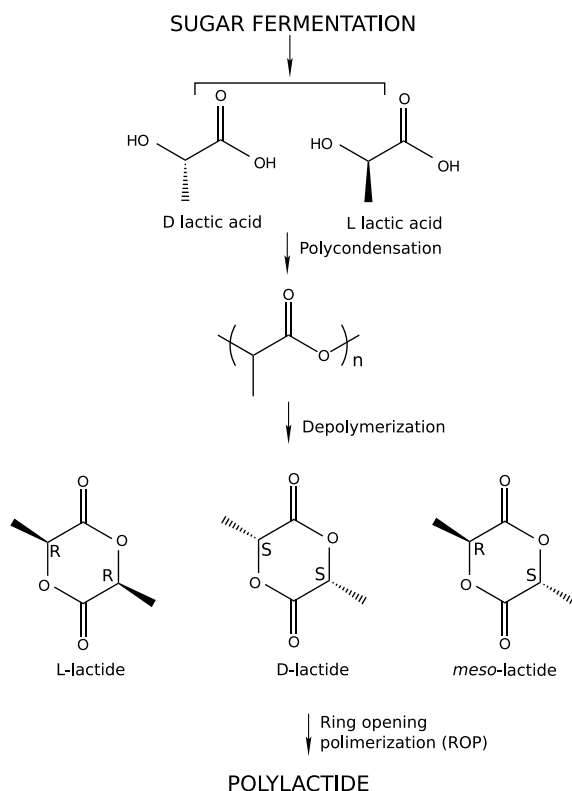


FIG. 3. Synthesis route of PLA from renewable biomass [96].

PLA, or aliphatic thermoplastic polymer (Fig. 4), has attracted significant attention due to its renewable sources, such as biomass derived from agricultural waste [96, 97]. As a biopolymer, PLA is fully biodegradable, bioabsorbable, biocompatible, and low-toxic [98]. Other advantages of PLA include low energy consumption and minimal greenhouse gas emissions during production. Its abundant availability, environmental friendliness, antibacterial properties, and good mechanical and thermal performance, make it a promising choice for sustain-

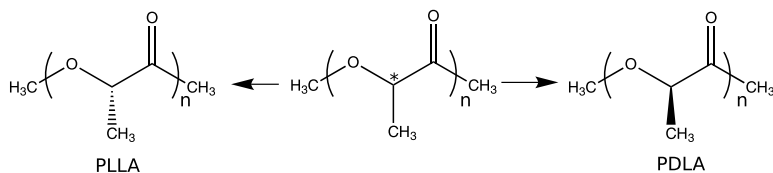


FIG. 4. Chemical structure formula of PLA [10].

able products. However, PLA has some drawbacks, such as low barrier properties, limited thermal resistance, and a low glass transition temperature [74, 99]. Therefore, suitable modifications are required to enhance the quality of PLA composites for wastewater treatment. Several studies have reported the production of composite films using PLA combined with various modifications. These modifications include the addition of fillers [100], chemical additives as crosslinking agents [101], and the addition or immobilization of nanoparticles [102]. These modifications improve PLA's efficiency in wastewater treatment, providing more environmentally friendly and sustainable solutions compared to petroleum-based synthetic polymers.

### 3. MODIFICATION OF PLA FOR WASTEWATER TREATMENT

Although PLA offers notable benefits such as excellent biocompatibility, ease of processing, and biodegradability, its application in fields like structural engineering remains limited due to certain drawbacks. These include brittleness at room temperature, low impact toughness, and relatively high production costs. Enhancing these properties through advanced modification methods can significantly improve PLA's performance and expand its applicability [103]. This review explores and summarizes various modification methods reported by researchers, as presented in Table 2. These modifications include surface chemical, physical, biological, and thermal modifications, nanoparticle incorporation, and bacterial immobilization, as depicted in Fig. 5. One approach involves developing PLA microspheres grafted with chitosan, which improves hydrophilicity and surface roughness, thereby enhancing the attachment and activity of nitrifying bacteria for ammonia removal [104].

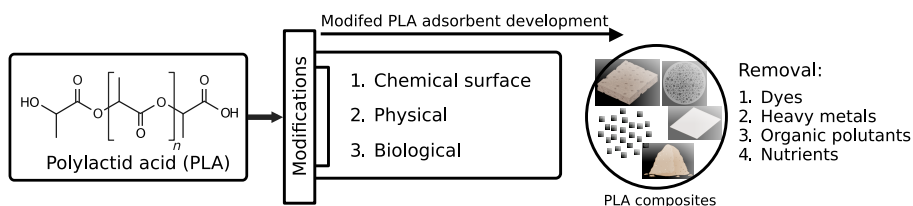


FIG. 5. Modification of PLA composite and its application to wastewater treatment.



TABLE 2. Summary of PLA modification studies and their applications in wastewater treatment.

Adsorbent	Modification	Adsorbates	Removal	References
PLA/TiO <sub>2</sub>	TiO <sub>2</sub> nanoparticles immobilization	Dye (C.I. Acid Orange 7)	Complete discoloration after 240 min	[17]
PLA membranes	Additive manufacturing	Various nutrients	90–98%	[18]
3D-printed PLA scaffold	Surface treatment with graphene oxide (GO)	MB	75%	[63]
PLA/C20A nanoclay	Ultrasound-assisted melt extrusion	Uremic toxins (uric acid, creatinine, urea), MB	Uric acid: 70% Creatinine: 89% Urea: 65% MB: 97%	[65]
Electro spun PLA/PEG-PPG-PEG/SiO <sub>2</sub> nanofibrous adsorbents	Blending with PEG-PPG-PEG and SiO <sub>2</sub>	Cu <sup>2+</sup>	88%	[66]
PLA/cellulose beads	One pot synthesis	MB	86.19 mg/g	[67]
PLA microsphere	Ammonolysis, hydroformylation, grafting with chitosan	Ammonia	NA	[104]
PLA/silica composites	In situ ring-opening polymerization (ROP)	Pb(II), Co(II), Cu(II)	90% for Pb <sup>2+</sup>	[105]
PLA/SA/CNP beads	Dissolution techniques	MB	94.25% 304.88 mg/g	[106]
3D printed PLA-HAp	Solvent-assisted blending and thermally induced phase separation (TIPS)	Cd, Pb	Cd: 360.5 mg/g <sub>HAp</sub> Pb: 112.1 mg/g <sub>HAp</sub>	[110]
3D printed PLA@CS/HAp composites	Monolithic PLA@CS/HAp filters utilizing 3D printing and freeze-drying techniques	Cu <sup>2+</sup>	90% (2-h adsorption) 80.8% (less than 35 min)	[111]
PLA microplastics	Hydrothermal aging	Pb <sup>2+</sup>	1058.03 µg/g	[112]
PLA/polyethyleneimine	Polydopamine-assisted grafting	Methyl Orange (MO) Cr(VI)	MO: 612 mg/g Cr(VI): 398.41 mg/g	[125]

TABLE 2. [Cont.].

Adsorbent	Modification	Adsorbates	Removal	References
PLA	None	Chlorinated phenols (CPs)	NA	[126]
PLA-nanocomposite	Blending PLA biopolymer/ silica nanoparticles (SNPs)	Oil & grease (O&G), Iron, Manganese TDS, Turbidity	O&G: 98.6% Iron: 22.56% Mn: 14.17% TDS: 11.33% Turbidity: 89.15%	[127]
BPBs-PLA	None	Cu Ni Pb Zn	Cu: 791.48 mg/kg Ni: 60.88 mg/kg Pb: 1414.58 mg/kg Zn: 295.17 mg/kg	[128]
EVA/PLA/SB	Melt mixing	Pb	58.8 mg/g	[129]
PLA/activated carbon beads	Phase inversion technique	Pb <sup>2+</sup>	202.81 mg/g	[130]
PLA-based surface	PLA modified with COOH and CONH <sub>2</sub> functional groups	Collagen	1522.2 ng/cm <sup>2</sup>	[131]
PLA/GO/PDA	Electrospinning	MB	98.81%	[132]
3D printing TCNF/PLA and ChNF/PLA filters	PLA reinforced with homogenously dispersed TEMPO-oxidized CNF or ChNF	Cu <sup>2+</sup>	TCNF: 234 mg/g <sub>NF</sub> (54%) ChNF: 208 mg/g <sub>NF</sub> (35%) Pure PLA (26%)	[133]
Pristine PLA MPs and PE MPS	Exposed PLA and PE mulches outdoors for 16 months, MPs generated from pristine and weathered mulches	Cd	Pristine PLA MPs: 106–126 mg/kg Pristine PE MPs: 23.2 mg/kg	[134]
Pure-PLA MPs aging PLA PPDMPs	Aging process	Organic pollutants	Pure-PLA MPs: 88% PLA PPDMPs: 64% and 56%	[135]
PLA foams	Modified supercritical CO <sub>2</sub> foaming	Various oils	CCl <sub>4</sub> : 26.1 g/g Diesel: 15.8 g/g Cyclohexane: 11.1 g/g Peanut oil: 20.8 g/g Silicone oil: 16.9 g/g	[136]
PLA-MPs biofilm	PLA-MPs undergo microbial colonization	Cu(II)	PLA-MPs: 1045.670 µg/g Pristine PLA MPs: 151.802 µg/g	[137]

TABLE 2. [Cont.].

Adsorbent	Modification	Adsorbates	Removal	References
Nano-porous PLA microfibers	One-step rotary centrifugal spinning	Oil	26.78 g/g	[138]
Commercial PLA-spoon MPs	Reduced PLA-spoon plastics	Pb <sup>2+</sup> Zn <sup>2+</sup> Cd <sup>2+</sup> Cu <sup>2+</sup> Ni <sup>2+</sup>	Pb <sup>2+</sup> : 1785 µg/g Zn <sup>2+</sup> : 1267 µg/g Cd <sup>2+</sup> : 748 µg/g Cu <sup>2+</sup> : 735 µg/g Ni <sup>2+</sup> : 722 µg/g	[139]
Commercial PLA-egg carton MPs	Reduced PLA-egg plastics	Pb <sup>2+</sup> Zn <sup>2+</sup> Cd <sup>2+</sup> Cu <sup>2+</sup> Ni <sup>2+</sup>	Pb <sup>2+</sup> : 1520 µg/g Zn <sup>2+</sup> : 1118 µg/g Cd <sup>2+</sup> : 423 µg/g Cu <sup>2+</sup> : 1408 µg/g Ni <sup>2+</sup> : 1412 µg/g	[139]
PLA/rGO	Solvothermal process	Fluoride, DB-53 dye	Fluoride: 173.1 mg/g DB-53 dye: 37.78 mg/g	[140]
PLA/MXene	Electrospinning technology	Ni <sup>2+</sup>	37.97 mg/g	[141]
PLA/AC beads	Phase inversion technique	Rhodamine B	149.57 mg/g	[142]
PLA-Zein/BU MoS <sub>2</sub>	Blow spinning, spray modification with butylated urea (BU); hydrothermal synthesis	MB	98.2% 111.2 mg/g	[143]
Foam-PLA/CGF	Tandem freezing-solvent replacement method	Oil	48.3 g/g	[144]
PLA/PBS-foam	Supercritical CO <sub>2</sub> foaming technology	Oils	7.9–21.9 g/g	[145]
PLA-chitosan nanocomposite	Gelation method	Urea	50.16%	[146]

Remarks: 3D – 3-dimensional; NA – not analyzed; TDS – total dissolve solid; HAP – hydroxyapatite; PLA – poly-lactic acid; SA – sodium alginate; CNP – carbon nanoparticles; EVA – ethylene vinyl acetate; SB – sugarcane bagasse; PDA – polydopamine; TCNF – TEMPO-oxidized cellulose nanofibers; ChNF – chitin nanofibers; PE – polyethylene; MPs – microplastics; PPDMPs – plastic product-derived microplastics; BPsBs – biodegradable plastic bags; rGO –reduced graphene oxide; MXene – conductive and hydrophilic 2D material; CGF – *calotropis gigantea* fiber; PBS – poly(butylene succinate).

### 3.1. Chemical modification

The synthesis and application of polymeric nanocomposite materials incorporating PLA and modified nano clay (Cloisite 20A, or C20A) treated with 1,4-diaminobutane dihydrochloride were investigated at varying reaction times. Nanoclay concentrations in the PLA matrix were 0.5%, 1%, and 5% (wt%). Thermal analysis indicated that the sample treated for 120 minutes (C20AM 120) exhibited the highest degree of modification, based on weight loss measurement. Fourier transform infrared (FTIR) analysis revealed a signal at  $1443\text{ cm}^{-1}$ , suggesting intercalation of the organic modifier between the clay galleries. Further characterization using X-ray diffraction (XRD), scanning electron microscope (SEM), and X-ray photoelectron spectroscopy (XPS) confirmed good dispersion of nanoclays at lower concentrations in the PLA matrix. Adsorption studies demonstrated that the PLA/C20AM 5% nanocomposite achieved the highest removal percentages, reaching 65–89% for uremic toxins and 97% for MB, indicating a strong affinity between the modified nano-clay and nitrogenous compounds. Adsorption was completed within 60 minutes at an optimal pH of 8, and the adsorption behavior was best described by the Langmuir isotherm model [65].

Another study focused on the synthesis of PLA/silica composites through in situ ROP of L-lactide onto the surface of pristine (Silochrom) and amine-functionalized (Silochrom-NH<sub>2</sub>) silica. FTIR spectroscopy confirmed successful grafting of PLA onto the silica surfaces. Thermal analysis showed that PLA accounted for 5.9% and 7.5% of the composite mass for Silochrom/PLA and Silochrom-NH<sub>2</sub>/PLA, respectively. The adsorption properties of these composites were evaluated for Pb(II), Co(II), and Cu(II) ions, considering variables such as contact time, initial metal ion concentration, and pH. Notably, Silochrom-NH<sub>2</sub>/PLA demonstrated a higher adsorption capacity of 1.5 mmol/g (90% removal efficiency) for Pb(II). The composites performed optimally at neutral or near-neutral pH (buffer pH 6.86) within the first 15 minutes of contact time. Adsorption equilibrium was best described by the Langmuir isotherm model, outperforming Freundlich or Temkin models [105].

A study conducted by Fathy *et al.* [106] investigated the adsorption of MB using novel bio-polymeric matrices prepared from PLA/sodium alginate (PLA/SA) and PLA/SA/carbon nanoparticle (PLA/SA/CNP) beads. The adsorbent was characterized by SEM and FTIR spectroscopy. The percentage of dye adsorbed increased with higher carbon nanoparticle (CNP) content, with the optimal concentration found to be 5% wt. Adsorption efficiency and capacity of the beads were evaluated by varying adsorbent dosage, initial pH, contact time, and adsorbate concentration. Maximum adsorption occurred at pH 9 after 120 minutes using 50 mg of PLA/SA/CNP beads. Experimental data were mod-

eled using the Langmuir and Freundlich isotherms, with the Langmuir model indicating the highest adsorption capacity at 304.88 mg/g. The beads demonstrated effective removal of MB dye, indicating strong potential for industrial wastewater treatment applications

MODOLON *et al.* [107] examined the influence of chitosan (CS) on the morphological, chemical, and physical properties of PLA-based electrospun membranes and their adsorption behavior in multielement aqueous systems containing  $\text{Cr}^{6+}$ ,  $\text{Cu}^{2+}$ ,  $\text{Zn}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Ni}^{2+}$ , and  $\text{Cd}^{2+}$  at pH 4. The addition of chitosan reduced fiber and pore diameters, resulting in enhanced mechanical properties, with modulus of elasticity reaching up to  $346.4 \pm 61.4$  MPa and tensile strength of  $4.57 \pm 0.69$  MPa. Contact angles varied between  $70 \pm 5^\circ$  and  $114 \pm 3^\circ$ , depending on membrane surface (smoother or rougher). In adsorption tests,  $\text{Cr}^{6+}$  removal efficiency was the highest (40–100%), with its adsorption increasing significantly due to the contribution of amino and oxygen-rich functional groups in CS with the  $\text{-COO}^-$  sites from PLA chains. SEM-EDS and XPS analyses further indicated that the smaller ionic radius of  $\text{Cr}^{6+}$  contributed to its more efficient removal [109].

In the study by STANDAU *et al.* [108], PLA was extensively reviewed for its potential as a renewable and biodegradable alternative to petroleum-based polymers such as polystyrene (PS). The research highlighted the primary limitation of PLA – its low melt strength – which poses challenges for foaming processes. To address this, researchers have incorporated various modification techniques, such as chain extension, branching, and cross-linking, into PLA, to improve its melt strength and make it more suitable for foaming processes. These modifications significantly enhanced PLA's rheological and thermal properties, enabling its use in conventional foaming methods, including batch foaming, foam extrusion, foam injection molding, and bead foaming. The study provided a comprehensive summary of chemical modifiers and their effects on PLA's foaming behavior, showcasing its adaptability for industrial applications. Although the research focused on foaming applications, incorporating chemical modifications introduced functional properties that could be beneficial for other applications, such as adsorption.

Similarly, ABDULKAREEM *et al.* [109] demonstrated the modifications of PLA surface using plasma-initiated grafting reactions with food additives such as ascorbic acid (ASA) and fumaric acid (FA). This approach aimed to enhance the surface and adhesion properties by grafting ASA and FA onto PLA after activating its surface with plasma. Analytical techniques such as FTIR spectroscopy and peel resistance measurement confirmed successful grafting and significantly improved aluminum foil adhesion, with peel resistance increasing by 74% and 184% for ASA- and FA-modified PLA, respectively [109]. Although this work focused on improving adhesion properties, the hydroxyl and carboxy groups in-

roduced by ASA and FA could be further explored for adsorption applications due to their potential interaction with contaminants.

The techniques described above, especially the incorporation of chemical modifiers and plasma-initiated grafting, can introduce functional groups or provide active sites that enhance PLA's adsorption capacity. These modifications increase the PLA-based materials' hydrophilicity, mechanical strength, and adsorption capabilities, resulting in increased pollutant removal efficiencies. The development of PLA composite fibers through such chemical modification methods showcases PLA's potential as an environmentally friendly and sustainable solution for wastewater treatment applications.

### 3.2. Physical modification

Previous studies have demonstrated the use of 3D printing technology to create structured adsorption filter materials by incorporating graphene oxide onto a PLA scaffold, significantly improving MB adsorption with a removal efficiency of 75% [63]. Another study reported that 3D printing technology also yields significant results. Modifications to PLA can enhance the performance characteristics of the composite, such as increasing adsorption capacities, improving selectivity, and strengthening structural integrity. One study demonstrated that modifying PLA with hydroxyapatite (HAp) significantly enhanced the biofilters' heavy metal adsorption capabilities, showcasing the performance benefits of material modification [110]. Additionally, a 3D-printed filter composed of PLA modified with CS/HAp composites results in filters with exceptional capabilities in removing heavy metals from water, as demonstrated by the remarkable efficiency in removing copper ions within a short duration of 90% removal within 2 hours, making it effective for rapid heavy metal removal from water [111]. Furthermore, hydrothermal treatment of PLA microplastics has been found to increase their adsorption capacity for heavy metals, such as lead, by modifying the surface characteristics and increasing the number of functional groups [112].

Several studies have demonstrated the potential of physical modification techniques, particularly plasma treatment, to enhance polymer properties, with significant implications for wastewater treatment applications. DUAN *et al.* [113] highlighted plasma techniques as an environmentally friendly and efficient method for modifying adsorbents to improve their pollutant entrapment capabilities. Their study emphasized plasma-induced functionalization, where various reactive groups are grafted onto adsorbent surfaces, significantly enhancing their adsorption of both organic and inorganic water contaminants. These advancements provide a sustainable approach for water quality improvement, aligning well with the growing demand for eco-friendly materials in environmental remediation.

Similarly, ZHIANMANESH *et al.* [114] explored plasma-based technologies as dry, reagent-free methods for surface biofunctionalization, overcoming the drawbacks of traditional wet chemical approaches. Their study demonstrated how plasma techniques can covalently immobilize biomolecules onto material surfaces, improving biocompatibility and enabling applications in biomedical devices. While focused on biomedical interfaces, the principles of plasma-induced functionalization, such as enhanced surface energy and the introduction of functional groups, can be adapted for wastewater treatment. In this context, biofunctionalized materials may facilitate selective adsorption or catalysis of waterborne pollutants.

BHATT *et al.* [115] provided further insights into the use of plasma treatment in modifying natural polymers, particularly for drug delivery systems. Their study demonstrated how plasma modification introduces functional groups to enhance surfaces wettability, adhesion, and loading capacity of natural polymers. These modifications improved the polymers' physicochemical properties and expanded their applicability in controlled drug delivery. By analogy, plasma-modified natural polymers could serve as advanced adsorbents with customized functionalities, enabling the targeted removal of specific contaminants, such as heavy metals or organic pollutants.

REZAEI *et al.* [116] demonstrated that atmospheric-pressure argon plasma submerged in the liquid phase effectively modifies the physical properties of PLA spinning solutions, enabling the production of smooth, uniform, and bead-free PLA nanofibers, an outcome not achievable using untreated PLA solutions. This improvement in PLA electrospinnability is primarily attributed to a plasma-induced increase in solution conductivity and viscosity, along with alterations in surface tension. As observed through SEM, the resulting nanofibers, exhibited improved morphology and uniformity. Making them highly suitable for adaptation in wastewater treatment applications. Additionally, plasma treatment process introduced functional groups and tailored porosity, further improving pollutant interaction and adsorption capability.

Another study reported that plasma-treated PVA/PLA composite membranes, initially designed to enhance hemostatic performance [117], hold significant potential for wastewater treatment. Plasma modification improved interfacial bonding, reduced fiber diameter, and increased surface roughness, resulting in membranes with superior liquid-enrichment capacity and improved structural integrity. These improvements, combined with the introduction of oxidized functional groups during plasma treatment, make the membranes highly effective in pollutant interaction and adsorption. The enhanced surface area and mechanical strength provide a robust platform for capturing and retaining contaminants in aqueous environments. By adapting plasma treatment to tailor functional groups specific to wastewater pollutants, these biodegradable and

eco-friendly composites offer a sustainable and advanced solution to environmental remediation challenges.

Collectively, these studies underscore the versatility of plasma treatment as a modification tool for polymers, especially PLA. In wastewater treatment, plasma-induced functionalization can significantly improve polymers' adsorption capacity and selectivity, providing a sustainable and efficient strategy for industrial wastewater treatment.

### 3.3. Biological modification

While the development of PLA-based composites incorporating proteins, amino acids, and microorganisms is still relatively limited, significant advancements have been made in modifying PLA for biomedical applications, tissue engineering, and surface functionalization. Biological modification of PLA can introduce functional groups that enhance its performance, particularly for wastewater treatment. To improve the surface functionality of PLA, MA *et al.* [118] grafted poly(hydroxyethyl methacrylate) (PHEMA) or poly(methacrylic acid) (PMAA) onto PLA films via photooxidation and UV polymerization techniques. These grafted polymers introduced hydroxyl and carboxyl groups, which were then activated to covalently immobilize gelatin and collagen. This modification improved PLA's hydrophilicity and introduced active binding sites. Their findings show potential for adapting PLA composites in the adsorption and removal of organic pollutants and bioorganic contaminants from wastewater.

Building on this approach, GU and CATCHMARK [119] demonstrated that proteins such as casein can act as dispersants to improve the compatibility of cellulose nanowhiskers (CNWs) in PLA composites. The functionalized CNWs enhanced both the dispersion properties and mechanical strength of PLA while maintaining its environmental compatibility. These improved interfacial interactions suggest that PLA-casein-CNW composites could provide active binding sites for hydrophilic contaminants, such as organic dyes or suspended proteins, making them suitable for usage in industrial wastewater systems.

Another study reported by PELLIS *et al.* [120] introduced a novel enzymatic approach for surface functionalization of PLLA films using hydrolytic enzymes such as *Candida antarctica* lipase B and *Humicola insolens* cutinase. This process successfully introduced reactive groups on the PLLA surface without altering its bulk properties, as demonstrated by a reduction in water contact angle from 74.6° to 33.1°, indicating improved hydrophilicity. Furthermore, XPS analysis confirmed successful grafting of functional molecules, enhancing biocompatibility and antioxidant activity. Their study highlights enzymatic modification as a nondestructive, eco-friendly alternative to chemical methods, with strong potential for improving PLA surface properties [120]. Simi-



larly, LEE and YEO [121] employed the proteolytic enzyme Alcalase from *Bacillus licheniformis*, to enhance the hydrophilicity of PLA fabrics. Under optimized conditions, enzymatic treatment induced structural modifications, as evidenced by a new peak at  $2\theta = 18.5$  in XRD, without compromising mechanical integrity of fabrics. This treatment also improved moisture regain and dyeing properties, making the PLA fabrics more versatile for textile applications. Collectively, these studies illustrate the versatility of enzymatic methods in tailoring PLA's properties and emphasize their application across diverse fields, including wastewater treatment.

Further advancing the functional versatility of PLA, HUANG *et al.* [122] modified PLA films with plasma treatment to introduce carboxylic acid groups, enabling the covalent grafting of antibacterial agents such as nisin and  $\epsilon$ -polylysine. These biopolymer-functionalized PLA films inhibited bacterial growth and enhanced surface bioactivity. Such modifications highlight potential for wastewater applications where microbial contamination must be controlled alongside the adsorption of organic and bioorganic pollutants. CALZONI *et al.* [123] explored the covalent immobilization of proteases from *Aspergillus oryzae* onto PLA, creating a porous structure for enzymatic hydrolysis. This modification enabled PLA to hydrolyze proteins in waste biomass, demonstrating its suitability for breaking down organic contaminants in wastewater. The immobilized enzymes exhibited notable stability and recyclability, further supporting their feasibility for large-scale wastewater treatment processes.

Finally, OZALTIN *et al.* [124] immobilized antibacterial compound chlorhexidine onto PLA using plasma activation and carbodiimide chemistry. This functionalized PLA exhibited improved hydrophilicity, cytocompatibility, and antimicrobial properties, making it effective against bacterial contaminants in aqueous systems. Their study reinforces the adaptability of PLA for wastewater treatment applications, especially in managing microbial pollution alongside organic contaminants. Together, these studies demonstrate the remarkable versatility of PLA modifications in enhancing its physicochemical properties, biocompatibility, and functional active sites. By incorporating proteins, amino acids, and antibacterial agents, PLA-based composites become more environmentally compatible and more effective in addressing critical challenges in wastewater treatment.

In this review, we also offer several recommendations for various methods that can be used to modify PLA for wastewater treatment, as shown in Table 3. These recommendations are expected to enhance the adsorption capacity of PLA and provide solutions for enhancing its capacity to adsorb contaminants in industrial wastewater.

TABLE 3. Recommendations for PLA modification using various methods and its application for wastewater treatment.

Adsorbent	Modification	Treatment
PLA powder	Surface functionalized with amino groups	Heavy metals
PLA film	Fabrication of glycine-chitosan/PLA	Dye
PLA film	Composite with carbon nanotubes	Heavy metals
PLA powder	Mixed with biochar	Nutrient
PLA film	Doped with TiO <sub>2</sub> or ZnO or other nanoparticles	Turbidity, heavy metals
PLA powder	Esterification and grafting with acid/base	Dyes/organic pollutant
PLA beads	Magnetic PLA-glycine-PEGDE (Fe <sub>3</sub> O <sub>4</sub> /PLA-g-P)	Heavy metals
PLA film	Grafting glycidyl methacrylate (GMA) (PLA-g-GMA)	Dyes, heavy metals

4. PLA VS OTHER ADSORBENTS

This review also compares the PLA performance as an adsorbent with other adsorbents, as summarized in Table 4. PLA adsorbents have several advantages and disadvantages compared to conventional adsorbents such as activated carbon and zeolite. One of the primary benefits of PLA is its biodegradability and derivation from renewable resources like sugarcane and corn [147, 148]. Meanwhile, activated carbon and zeolite require energy- intensive production processes and can pose environmental challenges during their manufacture, usage, disposal, and recycling [149]. However, pure PLA often exhibits lower physicochemical properties and adsorption capacities [150] compared to activated carbon and zeolite known for their exceptionally high adsorption capacity [151]. Studies have shown that activated carbon and zeolite can effectively remove contaminants from laundry wastewater [152]. Zeolite is valued for its high cation exchange capacity and good thermal stability, but its higher cost and the risk of filtration system clogging pose challenges [153, 154].

PLA and bentonite, in their natural forms, exhibit distinct adsorption capabilities. Studies have shown that natural bentonite, with its high cation exchange capacity and porosity, is effective in adsorbing heavy metals and certain organic pollutants. However, its limitations in adsorbing hydrophobic and anionic dyes without chemical modification are well-documented [77, 78]. In contrast, unmodified PLA demonstrated its inherent advantages that enable adsorbing pollutants such as heavy metals and dyes, albeit at lower efficiency than modified forms. PLA’s structure contains functional groups that facilitate interactions with metal ions and dye molecules through hydrogen bonding and electrostatic interactions. These inherent properties make PA capable of adsorbing certain pollutants without modifications.

TABLE 4. Comparative advantages and disadvantages of PLA-based adsorbents versus other adsorbents reported in the literature.

Adsorbent	Advantages	Drawbacks	References
PLA	<ul style="list-style-type: none"> <li>• Biodegradable, derived from renewable sources, reducing its carbon print</li> <li>• Thermoplastics, easy to process and shape</li> <li>• Sustainable and renewable</li> </ul>	<ul style="list-style-type: none"> <li>• Poor mechanical properties, brittleness, low modulus of elasticity, and low tensile strength</li> <li>• Low adsorption capacity on pure form</li> </ul>	[66, 125]
Activated carbon	<ul style="list-style-type: none"> <li>• High adsorption capacity</li> <li>• Unique thermal and electrical properties</li> <li>• Micropore structure</li> </ul>	<ul style="list-style-type: none"> <li>• High cost</li> <li>• Limited number of reuse cycles</li> <li>• Non-biodegradable</li> </ul>	[176, 177]
Zeolite	<ul style="list-style-type: none"> <li>• High surface area</li> <li>• High cation-exchange capacity</li> </ul>	<ul style="list-style-type: none"> <li>• High cost</li> <li>• Potential for clogging in filtration systems</li> </ul>	[178, 179]
Bentonite	<ul style="list-style-type: none"> <li>• High porosity</li> <li>• Non-toxic properties</li> <li>• Natural availability and abundant</li> </ul>	<ul style="list-style-type: none"> <li>• Low affinity for hydrophilic azo dyes and anionic pollutants</li> <li>• Low adsorption capacity without modification</li> <li>• Low surface area in natural form</li> </ul>	[180, 181]
Nano-clay	<ul style="list-style-type: none"> <li>• High surface area</li> <li>• Potential for functionalization</li> <li>• High porosity</li> </ul>	<ul style="list-style-type: none"> <li>• Stability issues</li> <li>• Potential environmental impact of nanomaterials</li> </ul>	[155, 182]
Cellulose	<ul style="list-style-type: none"> <li>• Abundant</li> <li>• Biodegradable</li> <li>• High surface area</li> </ul>	<ul style="list-style-type: none"> <li>• Lower adsorption capacity without modification</li> <li>• High cost of isolation from biomass</li> <li>• Low mechanical properties</li> </ul>	[45, 183]
Chitosan	<ul style="list-style-type: none"> <li>• Biodegradable</li> <li>• High affinity for metal ions and organic pollutants</li> </ul>	<ul style="list-style-type: none"> <li>• Solubility in acidic media</li> <li>• Mechanical strength issues</li> <li>• Low adsorption capacity in natural form</li> <li>• Lack of selectivity</li> </ul>	[171, 184]
Starch	<ul style="list-style-type: none"> <li>• Biodegradable</li> <li>• Low cost</li> <li>• Abundant</li> <li>• Safe usage</li> </ul>	<ul style="list-style-type: none"> <li>• Lower adsorption capacity without modification</li> <li>• Lower mechanical strength</li> <li>• Slight water solubility</li> <li>• Limited thermal ability</li> <li>• Low surface area</li> <li>• Rapid degradability in water</li> </ul>	[185, 186]

Research has demonstrated that modifying PLA with nanomaterials such as bentonite nano-clays, enhances its adsorption capacities by combining the high surface area and porosity of nano-clays with the structural integrity and environmental benefits of PLA [65, 155]. This synergetic effect increases pollutant removal efficiency and addresses concerns related to nanomaterials' environmental stability and toxicity. These findings position modified PLA as a superior and sustainable alternative to bentonite for diverse environmental applications. For instance, a study on the tensile strength of pure PLA and PLA-bentonite nanocomposite indicates that incorporating bentonite into PLA enhances its mechanical properties, suggesting improved structural integrity for environmental applications [156]. Additionally, research on the adsorption properties of modified bentonite clay shows that while natural bentonite has a specific capacity for adsorbing toxic metals, chemical modification can significantly enhance this capacity [157]. A study by GOPAL *et al.* [158] highlights the enhancement achieved when iron (Fe) and lead (Pb) are deposited onto bentonite clay, demonstrating that the metals formed spherical particles with reduced aggregation. This modification significantly increased the specific surface area of the bentonite composite, resulting in a threefold increase in tetracycline removal efficiency compared to Fe/Pb without bentonite. This finding underscores the limitations of natural bentonite in its unmodified state, as it requires metal deposition to achieve such substantial improvements in adsorption capacity.

As a naturally abundant and biodegradable polymer, cellulose has been widely explored for its potential in environmental applications, particularly wastewater treatment [159]. However, traditional isolation/extraction methods from lignocellulosic biomass, which often involve harsh chemical treatment using strong acids and strong bases (commonly,  $\text{H}_2\text{SO}_4$ ,  $\text{HCl}$ ,  $\text{KOH}$ , and  $\text{NaOH}$ ), are associated with the generation of toxic by-products and environmental concerns [160]. The physical isolation method, while effective, requires significant energy input, posing challenges to sustainability and resulting in low-crystallinity cellulose [161]. Studies have reported that both methods are the most efficient for isolating cellulose from lignocellulosic biomass [162, 163], compared to other methods. PLA, meanwhile, has advantages in terms of diverse raw material availability, lower cost, and being more environmentally friendly during production [7].

In its pure form, cellulose often exhibits low adsorption capacities, which limits its effectiveness in various applications. However, modifying cellulose into composite aerogels has significantly improved adsorption performance. For instance, cellulose composite aerogels have achieved a maximum adsorption capacity of 406.89 mg/g for MB dye [164]. Similarly, cellulose aerogels have also been reported to exhibit a high adsorption capacity of 3429.23 mg/g for Congo red dye [165], highlighting their potential for dye removal in wastewater treatment.

The inherent hydrophilic nature of cellulose, which poses challenges in specific applications, has been effectively addressed through hydrophobic modifications. TOMKOWIAK *et al.* [166] demonstrated that cellulose could be hydrophobized using silanization and alkyl ketene dimer (AKD) techniques, significantly enhancing its performance in oil-water separation. These modifications enable treated cellulose sorbents to achieve remarkable oil sorption capacities, making them highly effective for mitigating oil spills. By leveraging these hydrophobic treatments, cellulose-based materials can overcome their natural limitations and offer tailored properties for specialized environmental applications. PLA offers a promising alternative to cellulose for environmental applications. Unlike cellulose, which is inherently hydrophilic and often requires extensive modification to improve its water resistance or oil sorption properties, PLA inherently exhibits these desirable characteristics. Its hydrophobic nature [167] makes PLA particularly suited for applications such as oil-water separation and wastewater treatment, where resistance to water absorption is critical. While cellulose modifications, such as silanization and alkyl ketene dimer (AKD) treatments, have been explored to enhance its functionality, PLA eliminates the need for such additional processing.

Additionally, combining cellulose with polylactic acid (PLA), a hydrophobic polymer, offers an innovative approach to creating composites with synergistic properties. PLA can act as the matrix while cellulose serves as the filler, or vice versa, resulting in materials with enhanced functionality. These cellulose-PLA composites are expected to exhibit new and improved properties suitable for various environmental applications, particularly wastewater treatment. This strategic modification addresses the limitations of both pure cellulose and PLA, aligning with the demand for sustainable and high-performance materials in environmental remediation [168, 169].

Chitosan is a biodegradable cationic polysaccharide, highly effective in removing various pollutants from wastewater due to the abundance of amino and hydroxyl groups in its structure [170]. However, studies have reported that chitosan suffers from low mechanical strength, lack of selectivity, low surface area, and solubility issues in acidic media (pH sensitivity) without additional modification [171]. PLA has been used to address these limitations. PLA modified with chitosan combines the advantages of both materials, resulting in adsorbents with high adsorption capacity and improved mechanical strength. For instance, PLA/chitosan nanocomposites exhibit high efficiency in removing cadmium ( $\text{Cd}^{2+}$ ) [51].

Starch is recognized for its biodegradability and non-toxicity, making it suitable for environmental applications. Although a cost-effective and biodegradable adsorbent, natural starch often exhibits slight water solubility, low thermal stability, rapid degradation in water, low surface area, lack of reaction functional

groups, and limited adsorption capacity without modification [172]. Its adsorption capacity can be significantly enhanced through modification. For example, REN *et al.* [173] reported that functional modification of starch enhanced its adsorption capacities nearly 10 times higher than natural starch-based adsorbent (118.92 mg/g compared to 12.60 mg/g for modified starch and natural starch, respectively). Although studies have also shown that starch-based adsorbents are eco-friendly and low-cost for pollutant removal [174], challenges remain in the isolation process, such as high energy input [175].

PLA can be transformed into composites with starch to enhance both adsorption capacity and mechanical stability. Evidence shows that using PLA as a composite matrix can address starch's drawbacks, such as high water solubility and low thermal stability. Moreover, modifications of PLA with fillers such as starch and the addition of supplementary materials such as organoclay are expected to provide more effective and sustainable solutions for wastewater treatment. This study indicates that modified PLA composites can compete with, and in many cases even outperform, other conventional adsorbents, offering sustainable solutions for wastewater treatment.

## 5. FUTURE PERSPECTIVES ON PLA COMPOSITES IN WASTEWATER TREATMENT

PLA composites in wastewater treatment are emerging as a promising and sustainable approach. However, several critical research areas must be addressed to harness PLA's potential in this field. This section highlights key future research directions to guide innovative and impactful studies.

### 5.1. *Advanced functionalization techniques*

Current studies have demonstrated the benefits of modifying PLA through chemical (acid/base), physical, and other methods. However, there remains substantial potential for advancing these functionalization techniques. Future research should explore innovative chemical grafting methods, plasma treatments, and the incorporation of multifunctional nanomaterials. For example, integrating graphene-based materials or metal-organic frameworks (MOFs) could provide synergistic effects, enhancing the adsorption of a wider range of contaminants.

### 5.2. *Mechanistic studies and modelling*

Understanding the adsorption mechanisms in PLA composites is crucial for optimizing their performance. Future studies should focus on detailed mechanistic analyses using advanced characterization techniques such as XPS, FTIR, and

nuclear magnetic resonance (NMR) spectroscopy. Additionally, developing predictive models for adsorption kinetics and isotherms specific to PLA composites will support the design of more efficient wastewater treatment systems.

### *5.3. Long-term stability and biodegradability*

One of PLA's primary advantages is its biodegradability. However, ensuring its long-term stability under various environmental conditions remains a challenge. Future research should investigate the degradation behavior of PLA composites under real-world wastewater treatment conditions, considering factors such as temperature, pH, and microbial activity. Developing strategies to balance biodegradability with mechanical stability, such as surface coatings or the incorporation of biodegradable stabilizers, will be crucial.

### *5.4. Scale-up and industrial applications*

Moving from laboratory research to industrial-scale applications requires addressing the scalability of PLA composite production. Future studies should develop cost-effective and scalable manufacturing processes including 3D printing and extrusion techniques. Collaborations with industry partners could facilitate testing PLA composites in pilot-scale wastewater treatment plants, providing valuable insights into their practical performance and economic feasibility.

### *5.5. Integration with existing treatment systems*

PLA composites have the potential to enhance existing wastewater treatment technologies. For instance, by combining PLA-based adsorbents with AOPs, including UV light-assisted or electrochemical AOPs, could create hybrid systems with superior contaminant removal capabilities [187]. Future research should explore the synergistic effects of such integrated systems and optimize their operational parameters.

### *5.6. Environmental impact and lifecycle assessment*

Assessing the environmental impact of PLA composites throughout their lifecycle is essential to ensure sustainability. Future studies should conduct comprehensive lifecycle assessments (LCA) to evaluate the environmental footprint associated with the production, use, and disposal of PLA composites. This approach includes analyzing energy consumption, greenhouse gas emissions, and potential environmental risks linked to degradation products.

## 6. CONCLUSIONS

PLA has emerged as a promising material for wastewater treatment due to its biodegradability, renewability, and versatility. However, its natural adsorption capacity is limited, necessitating modifications to improve its effectiveness. Various modification techniques, such as surface chemical changes, incorporation of nanomaterials, and electrospinning, have shown significant improvements in the adsorption capacity of PLA for various contaminants. These modifications have enabled PLA to efficiently remove heavy metals, organic dyes, and other pollutants, making it a viable option for sustainable wastewater treatment.

Despite these promising results, several challenges remain, including optimizing these modification techniques, developing novel composite materials, and assessing the long-term environmental impacts of modified PLA applications in wastewater treatment. Future research should focus on reducing production costs, enhancing adsorption capacity of PLA composites, and ensuring environmental safety and sustainability. This review provided a comprehensive overview of the current state of PLA in wastewater treatment, highlighting the need for continued research and development to harness its full potential in advancing environmental sustainability.

## CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

**Andriy Anta Kacaribu:** conceptualization, original draft writing, writing, revising, and editing.

**Yuliani Aisyah** and **Febriani Febriani:** supervision, reviewing, and editing.

**Darwin Darwin:** conceptualization, supervision, writing, revising, and editing the manuscript.

## DECLARATION OF COMPETING INTERESTS

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

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