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Mechanical properties of biocomposite from polylactic acid and natural fiber and its application: A Review study

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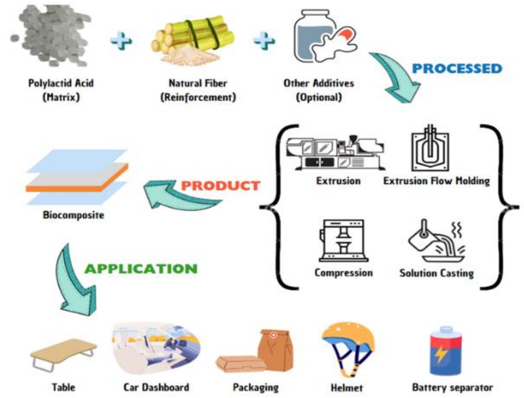

Highlights:

- PLA is a popular biocomposite, offering a sustainable alternative to petroleum-based plastics.
- Natural fiber selection affects strength and durability, impacting PLA biocomposite performance.
- Different manufacturing methods allow commercialization, but material challenges remain.

Abstract

In the past decade, the development of biocomposite materials has attracted much attention due to the growing concerns about petroleum-based natural resource depletion and pollution. Among the various biocomposite materials, polylactic acid (PLA) is one of the most widely produced and ideal for use in commercial products. The manufacture of PLA biocomposites with natural fiber reinforcement as an alternative material that replaces synthetic materials is widely researched. The different types of natural fiber sources used in the incorporation of matrix and fibers are very important as they affect the mechanical properties of the biocomposites. In addition, PLA-based biocomposites can be produced by a wide variety of methods that can be found in various commercializations. This study aims to present the recent developments and studies carried out on the development of PLA-based natural fiber biocomposites over the past few years. This study discusses PLA biocomposite research related to their potential, mechanical properties, some manufacturing processes, applications, challenges, and prospects.

Keywords: Polylactic acid; Natural fiber; Mechanical properties; Manufacturing

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1. Introduction

The development of biocomposites has become a trend in the last 10 years in various application fields such as packaging, household appliances, battery separators, and automotive components [1]–[5]. Biocomposites are considered to provide a transformation to materials that are more environmentally friendly than synthetic materials. This is because biocomposites are made from natural materials, so they are environmentally friendly. In addition, other advantages include low price, abundant availability, and competitive mechanical properties compared to synthetics [6]. The development of biocomposites is one of the efforts to utilize the potential of natural materials as well as minimizing agricultural waste and increase its use value [7].

Several biocomposite fabrication processes have been carried out by several researchers such as solution casting, injection molding, compression molding, and blow molding as shown in **Figure 1**. Of these types, solution casting is one of the simple and low-cost processes in producing bio-

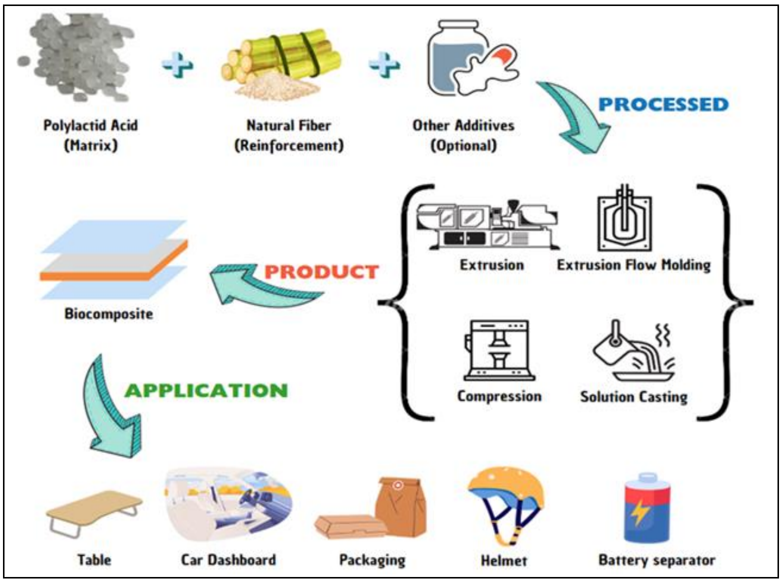

Figure 1. Fabrication of biocomposites and their applications

biocomposites [8]. For example: the development of biocomposites based on bengkuang starch and water hyacinth fiber using the solution casting process where starch and fiber are gelatinized at a temperature of about 60-80 °C. After that, the biocomposite gelatin mixture is molded by pouring into a glass mold. Solution casting is a lab-scale method for research [7], [9].

In addition, other methods such as injection molding, compression molding, and blow molding are methods that utilize direct heating of polymer seeds and molding according to the mold of the product. The processing heating temperature is about 130-180 °C depending on the type of polymer used [10], [11]. Biocomposite materials need to be tested for their properties, especially mechanical properties. It is used as a selection parameter suitable for biocomposite applications. For example: biocomposites based on PLA and sesame husk powder cellulose fibers are suitable for use as packaging [12].

The focus of this review is to comprehensively analyze the mechanical properties of natural fiber-reinforced PLA biocomposites sourced from various agricultural wastes. The mechanical properties in question are tensile strength, modulus of elasticity, and elongation at break. In addition, the results of the mechanical properties obtained will be further discussed, as well as their potential applications in various fields of human life.

2. Biocomposites

Biocomposites are materials composed of two or more materials, one of which is of natural origin. The main components in biocomposites are matrix as a binder and filler as a reinforcement [13]. The combination of matrix and filler is the key to improving the properties of biocomposites, such as mechanical properties. An illustration of a biocomposite when stretched for mechanical properties is presented in **Figure 2** where the constituent components consist of a matrix and reinforcement. Other substances are usually used as compatibilizer agents to improve the interfacial bonding of the two materials [14].

Matrices in composites generally consist of several types, namely polymer-matrix composites, metal-matrix composites, and ceramic-matrix composites [15]. Of these, biocomposites are usually composed of a polymer matrix. The main factors that can improve the mechanical properties of biocomposites include even dispersion of reinforcement, absence of clumping, and good bonding between matrix and reinforcement [16], [17].

Some biocomposite matrices that are often used include cellulose [18], protein [19], starch [20], chitosan [21], and polylactic acid [22]. Of these matrices, polylactic acid-based biocomposites are superior in terms of mechanical properties. Meanwhile, the filler used comes from natural fibers such as empty palm bunches [23], pineapple leaves [24], bamboo fibers [25], hemp [26], sugar palm [27], and other types. The cellulose content in natural fibers is one of the factors for good bonding between the matrix and fibers.

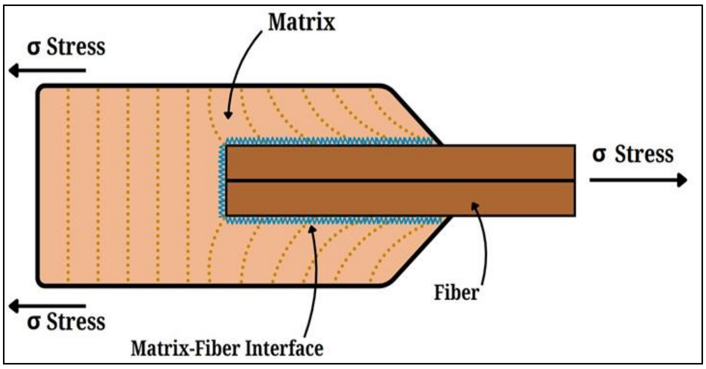

Figure 2. Illustration of stretched biocomposite components (matrix and reinforcement) in one system

3. Polylactic Acid

Biodegradable plastics are products that can be made from natural materials are a major concern in new developments, one of which is Polylactic Acid (PLA) [28]. Polylactic Acid (PLA) is one of the most in-demand types of biopolymers worldwide with total production reaching 211,000 tons in 2020 [29]. PLA is a type of thermoplastic polymer that is currently popular because it is derived from environmentally friendly materials and has good performance [30]. The potential of this material is an alternative solution to the problem of plastic pollution [31]. PLA can be produced through the fermentation process of materials such as corn, starch, potatoes, sugarcane, and other agricultural sources [32]. Also, it can be produced through direct polymerization or the ring-opening polymerization of lactic acid [33]. One of the advantages of PLA is good forming results and is suitable for use with various methods such as injection molding and film extrusion as well as its biodegradable nature [34]. The utilization of PLA is very broad, it can be applied in various fields such as packaging, automotive, and biomedical [35]. Despite its various advantages, PLA also has some disadvantages such as brittleness, hydrophilic properties, and low thermal stability [29].

Various efforts were made to improve the weaknesses of PLA's properties. PLA offers many advantages such as the degradability of CO_2 and H_2O in the natural environment and good biocompatibility [36]. Combining PLA with natural fibers shows good compatibility and offers several attractive advantages over conventional synthetic polymer composites, such as biodegradability, environmental friendliness, affordable cost, easy to find, and low density [37].

4. Natural Fibers

Natural fibers are materials obtained from the isolation of plants or animals that can be applied in various sectors, especially in textiles and biocomposite materials [38]. Natural fibers have several contents such as cellulose, hemi-cellulose, and lignin which have a structure as shown in **Figure 3**. One of the contents that affect the mechanical and physical properties of biocomposites is the cellulose content [39]. Cellulose is a long-chain polymer made up of carbon, hydrogen, and oxygen, with the chemical formula C6H10O5 [40]. The cellulose content varies significantly among different sources. For instance, cotton is nearly pure cellulose, making it ideal for high-quality paper [41]. In contrast, wood fibers typically contain 40% to 50% cellulose, depending on the species and even individual trees [42]. Cellulose derived from natural fibers can serve as reinforcement in biocomposites [43]. **Table 1** shows the cellulose content and other components of natural fibers from various sources that have the potential to become reinforcement for biocomposites.

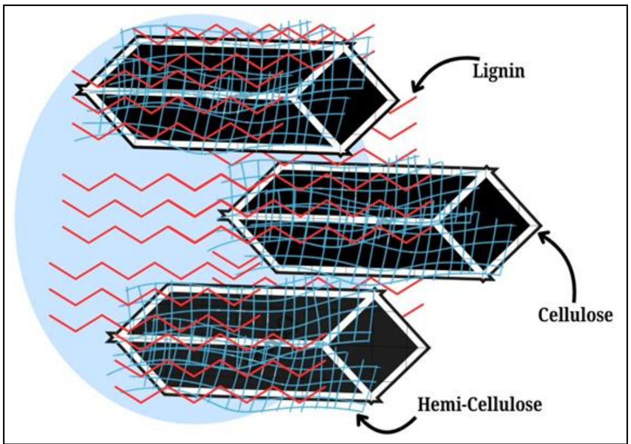

Figure 3. Natural Fiber Structures

Table 1. Chemical composition of some natural fibers

No	Fiber Sources	Cellulose (%)	Hemi-cellulose (%)	Lignin (%)	References
1	Wood (Softwood and Hardwood)	40 - 50	15 - 30	20 - 25	[42]
2	Bast Fibers (Hemp and Ramie)	68 - 91	5 - 16.7	0.6 - 10	[44]
3	Fruit Fibers (Oil-Palm Empty Fruit Bunch)	32.97 - 70.96	11.6 - 31.51	7.32 - 19.79	[45]
4	Grass Fibers (Sugarcane Bagasse)	42.40 - 58.86	18.79 - 25.20	17.60 - 19.70	[46]
5	Leaf Fibers (Abaca)	56 - 73.81	11.32 - 59	5 - 15.1	[47]

5. Mechanical Properties of Biocomposite based PLA and Natural Fiber

PLA-based biocomposites with natural fiber reinforcement are widely researched to create new biodegradable materials. Natural fibers are usually pre-treated both chemically and mechanically to produce quality fibers that can bind well with the PLA matrix. Chemically treated (alkalized) natural fibers are reported to have better tensile strength and elastic modulus than fibers without chemical treatment because alkalized fibers have good interfacial adhesion with PLA [48]. Alkalization makes the breakage of fiber bonds finer to support the improvement of the interface with the matrix so that the flexural strength of the biocomposite can also increase [49]. PLA-based hybrid biocomposites have also been reported to produce a material with high stiffness [50]. The main component of natural fibers often used as PLA reinforcement is cellulose, because cellulose has high crystallinity [51]. Cellulose can increase the sensitivity of the mechanical properties of PLA, although homogeneous blends are difficult to obtain. The hydroxyl groups at the ends of cellulose (**Figure 4**) are hydrophilic and have a variety of interfaces to PLA. This variation can cause an increase or decrease in mechanical properties towards PLA, depending on the adhesion between cellulose and the matrix formed [52].

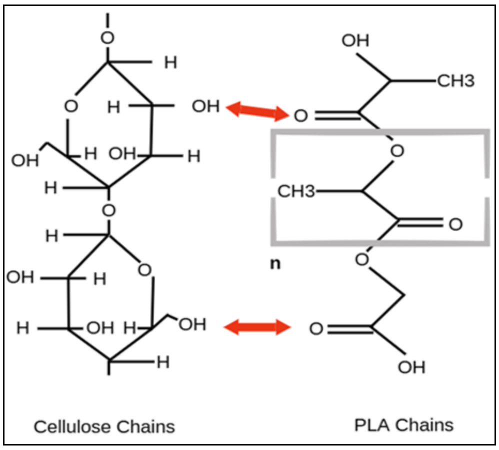

Figure 4. Natural Fiber Structures

Mechanical properties are important properties that must be known in a biocomposite because they present the final strength value of the biocomposite product [53]. Mechanical Properties of PLA-based Biocomposites with natural fiber reinforcement from various sources (**Table 2** and **Figure 5**) are listed to determine the final strength of biocomposite products made by several researchers.

Table 2. Chemical composition of some natural fibers

No	Biocomposites		Methods	Stress (σ) (MPa)	Modulus (E) (MPa)	Elongation (ε) (%)	Ref.
	Matrix	Filler					
1	PLA	Jute Fiber	Single Screw Extruder	33.29	1446.1	3	[54]
2	PLA	Flax Fiber	3D Printing	183	17200	1.5	[55]
3	PLA	Sisal Fiber	Injection Molding	54.9	5600	2.7	[56]
4	PLA	Sisal Fiber	Injection Molding	70.9	4700	2.3	[57]
5	PLA	Coconut Fiber (Coir)	Hot Pressing	49.73	9040	1.63	[58]
6	PLA	Bamboo Fiber	3D Printing	29.21	2360	2.43	[59]
7	PLA	Piper Betle Fiber	Solution Casting	26.34	166.46	16.85	[60]
8	PLA	Mango seed	Injection Molding	52.2	3280	2.2	[61]
9	PLA	Cellulose Nanowhisker from Napier	Solution Casting	21.22	11.35	6.17	[62]
10	PLA	Eucalyptus microfiber	Solution Casting	19.1	1700	5.1	[63]
11	PLA	Cellulose Nanofiber from Jute fiber	Solution Casting	35.61	-	-	[31]
12	PLA	Lemongrass Fiber	3D Printing	48.8	-	-	[64]
13	PLA	Cellulose Nanocrystal from Ramie Fiber	Single Screw Extruder	-	2033	-	[65]
14	PLA	Cellulose Nanofiber from Pineapple Crown leaves	Solution Casting	33.17	2620	9.14	[66]
15	PLA	Microfibril Cellulose from Curaua Fibers	Injection Molding	52.7	2530	-	[67]

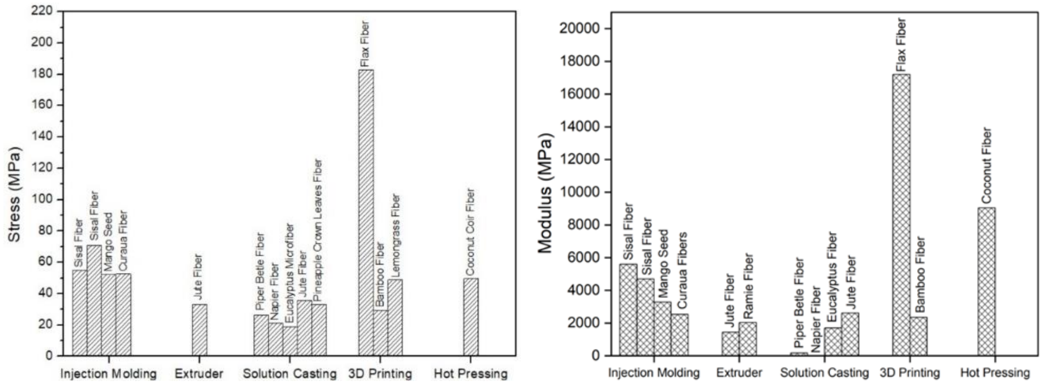

Figure 5. PLA-based biocomposites with reinforcement of various natural fibers in different manufacturing processes (graphic visualization based on references in **Table 2**)

6. Potential Application

The application of PLA biocomposites across various sectors is a significant focus of interest. Main advantages of PLA biocomposites enhanced with natural fiber reinforcement are their competitive strength and environmental friendliness compared to traditional synthetic materials. Previous research has highlighted several promising applications for these biocomposites, including food packaging [68], automotive components [69], household appliances [70], helmets [71], building panels [72], and more. With this wide range of applications, commercialization through industry into mass products is one of the potentials that can be developed. Biocomposite development has a bright future and contributes to the achievement of sustainable development goals.

7. Future Research

This biocomposite is one of the advanced material developments that has potential in various applications. Nowadays, exploration of biopolymer matrix materials as biocomposite matrix is the key to determining environmentally friendly properties and competitive cost in its maufacturing [73]. However, future research is recommended to focus on the performance of biocomposites through filler size engineering and improving the surface bond between the matrix and filler. One of the advanced research efforts is filler size engineering to the nanometer area. Nano filler or nano-sized filler is one way to increase the surface contact area between the filler and the matrix. With a wide contact area, biocomposites are expected to produce excellent properties, especially mechanical properties [74]. Meanwhile, another technique is to increase the bond between the matrix and filler. This technique can be accommodated through the ultrasonication bath process where the filler is assisted to be evenly distributed via sound waves [6], [9], [75].

8. Conclusions

Natural fiber-reinforced PLA biocomposites have great potential in meeting the needs in various fields as an environmentally friendly material worldwide. Methods usually used in the fabrication of PLA-based biocomposites reinforced with natural fibers include extrusion, blow molding, compression molding, and solution casting. The addition of natural fibers from various sources of agricultural waste is proven to improve the mechanical properties of PLA-based biocomposites which are suitable for application as food packaging materials, household appliances, building panels, and automotive components. On the other hand, by utilizing existing agricultural waste, it can support economic improvement because it converts useless waste into high-value composite reinforcement materials. With mechanical properties that are competitive with synthetic polymers and more environmentally friendly, this natural fiber-reinforced PLA biocomposite has great potential as a substitute for synthetic polymers that can be commercialized. Further research is needed especially in the development of more innovative fabrication methods of PLA-based biocomposites with natural fiber reinforcement to further enhance their potential in meeting the needs of material in various fields more easily, effectively, and environmentally friendly in a sustainable future.

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Authors' Declaration

Authors' contributions and responsibilities - Writing article review section and image illustration scheme design (M.A., R.R.P., M.Y.); Additional detailed and comprehensive reviews (C.D.M.D., R.A.I).

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

Additional information – No additional information from the authors.

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