Effect of lignin on morphology, biodegradability, mechanical and thermal properties of low linear density polyethylene/lignin biocomposites

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Abstract. This research is purposed to study effects of lignin compositions on morphology, biodegradability, mechanical and thermal properties of low linear density polyethylene (LLDPE)/Lignin biocomposites. LLDPE/Lignin biocomposites has been manufactured by adding LLDPE, lignin and compatibilizer into rheomix at 200°C with a stirring speed of 70 rpm for 30 min. The composition of lignin added was 5, 10, 15, and 20 phr with compatibilizer 5 phr. LLDPE/lignin films has been made by using hydraulic hot press at 200-210°C with pressure of 6 bar for 20 min. Fourier Transform Infrared (FTIR) spectrum analysis was conducted to determine the functional groups of LLDPE/Lignin biocomposites. The surface morphology was observed by using Scanning Electron Microscope (SEM). The mechanical properties was measured as a tensile strength and thermal stability was measured by Thermogravimetric Analysis (TGA). In addition, biodegradation test was also conducted to determine the level of biodegradability. TGA results indicated that at 456°C LLDPE and lignin had similar thermal stability and the addition of lignin into LLDPE/lignin biocomposites can reduce the thermal stability up to temperature of 450-460°C. However, the thermal stability is increased at temperature over 460°C. The tensile strength and elongation at break of all LLDPE/Lignin biocomposites at various compositions is lower compared to those of LLDPE. The more lignin were added into LLDPE/Lignin biocomposites, the more the materials were biodegraded.

1. Introduction

Research on utilization and development of polymeric materials based on the use of renewable natural resources as raw material for the polymer industry has attracted the interest in the past few decades. Basically, the development of renewable materials for polymer comes from two main problems, which are the environmental problem associated with waste generated and the limitation of natural resources derived from fossil materials. Both of these problems has driven the efforts to find alternative materials based on renewable and biodegradable natural resources which can reduce the dependency on petroleum based material and simultaneously can solve the environmental problem caused by the generated waste.

Some of biomasses that can be used as raw material of polymers are starch, lignin, cellulose, protein, chitosan, and some vegetable oils. Among them, lignocellulose is considered as one of the most potential alternative material because it does not intersect with food crops. Lignocellulose is generally derived from wood containing cellulose, hemicellulose and lignin. Availability of lignin...
reaches 30% of all non-fossil organic carbon on earth and commonly produced by paper industry in a significant quantity. The utilization of lignin as a new renewable biomaterial may be a perfect candidate for modification and chemical reactions due to its functional properties (rich in phenolic and aliphatic hydroxyl groups) for the development of new biomaterials. However, there is a major challenge in polymer applications associated with unclearly defined structure and diversity based on their origins, separations and fragmentation processes. Chemical modification of lignin can be classified into lignin fragmentation into phenolic or other aromatic compounds, synthesis of new chemical active sites and functionalization of hydroxyl groups [1].

Utilizations of lignin to produce biomaterial or biofuel have been previously performed [2-4]. Research on lignin in polyurethane applications have also been conducted [5-10,11-12]. Studies on chemical modification of lignin as biobased polymers [1,13,14], biodegradable [15], green composites [16] and green hydrogel [17] have also been reported. Various efforts have been reported to combine lignin into other natural polymers to form a full bio-based materials. There have been also reports on addition of lignin into starch, proteins, polycaprolactone, poly(hydroxyl-butyrates) [3,18], gelatin [19], polybutyleneadipate-co-terephthalate [20], chitosan [21], and polylactic acid [22-26]. The number of hydroxyl groups in the lignin causes a relative polar characteristic thereby providing better affinity to the polar polymer. However it also raises a problem when composited with nonpolar material because it is not compatible and will result in composites with poor stress transfer in terms of mechanical properties. Therefore, a compatibilizer to improve the inter-phases adhesion so that the material be compatible becomes necessary. Moreover, the compatibility of lignin can also be improved by reducing the content of hydroxyl, even simple esterification or alkylation of hydroxyl groups can favor the compatibility of lignin with non-polar polymer matrices [3]. Recent studies on utilization of lignin are more focused on the production of lignin-based thermoplastics. In addition, studies on performance of polymers and composites by mixing lignin or lignocellulosic material with thermoplastic resin has been reported [27-38]. Studies of the addition of the lignin into a non-biodegradable material are also intended to increase biodegradability of the resulted composites. Various studies on biodegradation of lignin have also been conducted [39-46].

In this research, LLDPE/Lignin biocomposites were manufactured by adding various composition of lignin into LLDPE to study the effects of lignin addition on the morphology, biodegradability, and mechanical and thermal properties of LLDPE/lignin biocomposites with polyethylene-grafted maleic anhydride as the compatibilizer. Lignin used in this research was a pure alkali lignin without modification.
2. Materials and Methods

2.1. Materials

The materials used in this study are a Linear Low Density Polyethylene (LLDPE) obtained from PT Chandra Asri, PE-g-MA as compatibilizer with viscosity of 500 cP (140°C) (lit.) and density of 0.92 g/ml (25°C) obtained from Sigma-Aldrich, and lignin with density of 1.3 g/mL (25°C) also obtained from Sigma-Aldrich, potassium dihydrogen orthophosphate (KH₂PO₄), magnesium sulfate (MgSO₄·7H₂O), ammonium nitrate (NH₄NO₃), sodium chloride (NaCl), ferrous sulfate (FeSO₄·7H₂O), zinc sulfate (ZnSO₄·7H₂O), manganous sulfate (MnSO₄·H₂O), potato dextrose agar, aspergillus niger, potassium monohydrogen orthophosphate (K₂HPO₄).

2.2. Composites and Films Preparation

LLDPE, lignin and PE-g-MA are mixed in advance to composite manufacturing. Those materials are stirred uniformly in Haake Rheomix PolyDrive. The composition of lignin added was 5, 10, 15 and 20 per hundred resin (phr) with the composition of compatibilizer was 5 phr. The mixture was processed in rheomix at 200°C with 70 rpm for 30 min. Chunks resulted from rheomix was then made into form of sheet using a Carver laboratory Hydraulic Hot Pressmodel 2702 at 210°C with a pressure of 6 bar for 20 min.

2.3. Characterizations

Analysis on functional groups of LLDPE, Lignin and LLDPE/Lignin bicomposite was conducted using FTIR at wave number of 4000-400 cm⁻¹. A total of 40 scans were accumulated in transmission mode with a resolution of 4 cm⁻¹. The morphological analysis of the LLDPE/Lignin bicomposite was investigated using a Scanning Electron Microscope (SEM) HITACHI SU3500. Thermal analysis was conducted using STA Linseis STAPT 1600. Biocomposites was heated up to 500°C with heating rate of 10°C/min in sample of small pieces with a weight of ± 20 mg. A universal testing machine (UTM) Strograph 50, Toyoseiki was used to evaluate the tensile strength dan elongation at break of LLDPE/Lignin biocomposites films according to ASTM D638. Biodegradation test was performed according to ASTM G 21-96. The medium for the fungi was prepared by dissolving KH₂PO₄ (0.7 g), MgSO₄·7H₂O (0.7 g), NH₄NO₃ (1.0g), NaCl (0.005 g), FeSO₄·7H₂O (0.002 g), ZnSO₄·7H₂O (0.002 g), MnSO₄·7H₂O (0.001 g) and agar (15 g) into 1L of water. Next step is the sterilization of agar medium by autoclaving at 121°C for 90 min. The sterilized agar medium is then poured into a sterile petri dish with depth of 3-6 mm and left until condensed. Samples biocomposites with size 2x2 cm² were planted on an agar medium, then added suspense fungus Aspergillus niger spores. Further, the samples were incubated for 68 days. The sample was then sterilized with alcohol 70%, then soaked in distilled...
water. Finally, the samples were dried at 50°C and then their dry weight were measured after biodegradation.

3. Results and Discussion

The composition of lignin added to LLDPE affects the color of LLDPE/Lignin biocomposites produced. The effect of lignin composition to the visual color biocomposite film is shown in Figure 1. The more lignin were added to the biocomposite then the darker the color of the produced LLDPE/Lignin biocomposites films. This is because the color of LLDPE used was translucent, whereas the lignin was dark brown. Therefore, the resultant composite tends to get darker with increasing lignin composition is added.

![Figure 1. LLDPE/Lignin biocomposite films](image)

3.1. FTIR Analysis

The FTIR spectrum of LLDPE, Lignin and LLDPE/Lignin biocomposites are shown in Figure 2. From the FTIR spectrum, it is shown that between LLDPE, lignin and LLDPE/Lignin have different absorption peak. LLDPE spectrum (Figure 2a) consist of -CH₂- and -CH₃ in its structure which were shown by absorption peaks at wave numbers of 2953-2841 cm⁻¹ which are antisym and sym CH stretching showing -CH₃ and -CH₂- groups in aliphatic compounds. Absorption peaks also appear at wave numbers of 1462 cm⁻¹ and 1456 cm⁻¹, which are a scissor vibration of CH₂ and antisym deformation of CH₃ associated with the CH₂ and CH₃ in aliphatic compounds, respectively. The absorption peak at wave number of 1369 cm⁻¹ shows C-C bonds while the absorption peak at wave number of 723 cm⁻¹ is attributed to CH₃ in methylene chains which indicating the group -(CH₂)ₙ- in hydrocarbons [47].
Meanwhile, the FTIR spectrum of lignin (Figure 2b) has specific absorption peak at wave numbers of 3396-3203 cm\(^{-1}\) which is OH stretch indicating the presence of hydroxyl groups. The absorption peaks at wave numbers of 2953 cm\(^{-1}\) and 2843 cm\(^{-1}\) are CH stretch that show -CH\(_3\) and -CH\(_2\) groups, respectively [22]. The absorption peaks at wave numbers of 1593 cm\(^{-1}\) and 1510 cm\(^{-1}\) are derived from C-C of aromatic skeleton vibrations, while the absorption peaks at wave numbers of 1458 cm\(^{-1}\) and 1425 cm\(^{-1}\) are attributed to the C-H deformation and C-H aromatic ring vibration [31]. The absorption peaks at wave numbers of 1269, 1134 and 1031 cm\(^{-1}\) are the deformation of C-O and C-H derived from syringyl and guaiacyl as lignin constituent monomers [22,25]. The FTIR spectrum of LLDPE/Lignin biocomposite (Figure 2c) showed has similar absorption peak with lignin, although the composition of lignin added into LLDPE is only maks 20 phr. It was indicated that absorption peak of LLDPE/Lignin biocomposite is mixture between absorption peak of LLDPE and lignin. Because of the –CH\(_2\) and –CH\(_3\) absorption peak of LLDPE was overlapped with the CH\(_3\) and –CH\(_3\) absorption peak of lignin, so it seems the absorption peak of lignin was dominant in FTIR spectrum of LLDPE/lignin composite. Nevertheless, the FTIR spectrum of LLDPE/Lignin composite showed a new absorption peak at wave number of 1730 cm\(^{-1}\) [48] indicating the presence of C=O group derived from the compatibilizer and OH absorption peak shifting and becoming increasingly sharp.
Figure 3 shows the FTIR spectrum of LLDPE/lignin biocomposites at various lignin composition. All of the spectrums of LLDPE/Lignin were almost similar and showed a new absorption peak at wave number of 1730 cm\(^{-1}\) indicating the presence of C=O group derived from the compatibilizer and OH absorption peak shifting and becoming increasingly sharp. The absorption peaks of LLDPE/lignin biocomposites that indicate certain functional groups are presented in Table 1.

### Table 1. Absorbance peaks of LLDPE/Lignin biocomposite

| Wavenumber (cm\(^{-1}\)) | Functional Group |
|--------------------------|------------------|
| 3365                     | -OH Lignin       |
| 2922                     | C – H LLDPE      |
| 2852                     | O – CH\(_3\) Lignin |
| 1730                     | C = O Compatibilizer |
| 1508                     | C = C Lignin     |
| 1458                     | -CH\(_3\) LLDPE  |
| 1381                     | C – C LLDPE      |
| 1267, 1217 and 1134      | C – O – C Lignin |

It is shown in Table 1 that all LLDPE/lignin biocomposites show absorption peaks at wavenumber of 2922 cm\(^{-1}\) indicating the presence of C-H, wavenumber of 1458 cm\(^{-1}\) indicating the presence of –CH\(_3\), and at wavenumber of 1381 cm\(^{-1}\) indicating the presence of C-C from LLDPE. Furthermore, all LLDPE/Lignin biocomposites show absorption peaks at 3365, 2852, and 1508 cm\(^{-1}\) indicating the presence of –OH, O-CH\(_3\), and C=C, respectively. In addition, the absorption peaks at wavenumber of 1267, 1217 and 1134 cm\(^{-1}\) indicating the presence of C-O-C from lignin. It is also shown that the absorption peak at wavenumber of 1730 cm\(^{-1}\) related to C=O from the compatibilizer. The appearances of those absorption peaks shows that the LLDPE/lignin biocomposites was successfully manufactured.
3.2. Thermal Properties

The effect of addition of lignin composition on the thermal stability of LLDPE/lignin biocomposites was studied by thermogravimetric analysis (TGA). TGA curves of LLDPE, lignin and LLDPE/lignin biocomposites are shown in Figure 4.

LLDPE, lignin and LLDPE/lignin biocomposites have a single degradation step. LLDPE starts degrading at 250-300°C, while the lignin starts degrading at 40°C and a major degradation occurs at 300-500°C related to fragmentation of inter-linkage units [25]. At temperature below 450-460°C, LLDPE/lignin biocomposites are more susceptible to degrade compared to LLDPE, however, they are more resistant to thermal degradation when compared with lignin. On the contrary, at temperature over 460°C, LLDPE/Lignin biocomposites are more resistant to thermal degradation than LLDPE, however, more susceptible to thermal degradation compared to lignin.

![Figure 4. TGA thermograms of (a) LLDPE; (b) LLDPE/Lignin 5 phr; (c) LLDPE/Lignin 10phr; (d) LLDPE/Lignin 15 phr; (e) LLDPE/Lignin 20 phr and (f) Lignin](image)

At 500°C the mass residu of LLDPE, LLDPE/lignin 5, LLDPE/Lignin 10, LLDPE/lignin 15, LLDPE/lignin 20 and Lignin are 2.58, 4.37, 8.73, 13.30, 17.33 and 41.39%, respectively. From the TGA curve of LLDPE and lignin, it is shown that at temperature over 450°C the thermal resistance of lignin was better than LLDPE which affects the thermal resistance of LLDPE/lignin biocomposites. The high thermal stability of lignin is caused by the presence of aromatic phenyl groups. In addition, the presence of hydroxyl groups also contributes to the thermal stability and improves the stability of aromatic structures in lignin and prevents damage due to temperature effects [22]. The increase in the residual mass is caused by the chemical structure of lignin, which shows a less contribution to the flammability of materials due to the high charring ability and the low heat release when burned [23,50]. This shows that the increase of lignin composition in the LLDPE/lignin biocomposites will
increase the char content [24,34,51] and the residual mass and will increase its thermal resistance as well. TGA results indicate that the addition of lignin into composite LLDPE/lignin biocomposites can reduce the thermal stability up to temperature of 450-460°C compared to LLDPE. The thermal stability curve of intersection between LLDPE (Figure 4a) and lignin (Figure 4f) shown at 456°C. This intersection curve show that at temperatures below 456°C LLDPE is more resistant to degradation than lignin, whereas the temperature above 456°C LLDPE more susceptible than lignin. Therefore, the composite of LLDPE and lignin will result in LLDPE/lignin biocomposites with a thermal stability which is lower than LLDPE, however, higher than lignin. The degradation thermal stability of LLDPE/lignin biocomposites is also allegedly due to the empty space in the LLDPE/lignin biocomposites which is filled with oxygen or air trapped. Subsequently, it will initiate the degradation process resulting in lower thermal stability [49]. However, the thermal stability LLDPE/lignin biocomposites is increased at temperature over 460°C compared to LLDPE. The increase in thermal stability of LLDPE/lignin is due to the appearance of complex phenylpropanoid unit containing aromatic phenyl groups from lignin. In addition, the presence of multiple hydroxyl groups also contribute in the improvement of the stability of aromatic structures within the structure of lignin so that it will increase the mass of the remaining. Furthermore, the presence of a hydroxyl group also contributes to the thermal stability because it increases the stability of aromatic structures present in lignin. The increase in the residue is due to the chemical structure of lignin indicating a less contribution to the burn-ability due to the high ability to become charcoal and low heat release when burned to prevent it from degradation because of the influence of temperature [22,23,50].

3.3. Mechanical Properties

The effect of the addition of lignin composition to the mechanical properties of LLDPE/lignin biocomposites was studied by analyzing the tensile strength and elongation at break. The analysis results of tensile strength and elongation at break are shown in Table 2.

The tensile strengths of LLDPE, LLDPE/lignin 5, LLDPE/lignin 10, LLDPE/lignin 15 and LLDPE/lignin 20 are 218.4, 109.7, 86.4, 98.2 and 105.6 kgf/cm², respectively. While the elongations at break of LLDPE, LLDPE/lignin 5, LLDPE/lignin 10, LLDPE/lignin 15 and LLDPE/lignin 20 are 1251, 55.1, 32.3, 37.1 and 40%, respectively. The tensile strength and elongation at break of all LLDPE/Lignin biocomposites at various compositions is lower compared to those of LLDPE [35,36].
Table 2. Mechanical properties of LLDPE/Lignin biocomposite

|                | Tensile Strength (Kgf/cm²) | Elongation at break (%) |
|----------------|----------------------------|-------------------------|
| LLDPE          | 218.4                      | 1251                    |
| LLDPE/Lignin 5phr | 109.7                      | 55.1                    |
| LLDPE/Lignin 10phr | 86.4                       | 32.3                    |
| LLDPE/Lignin 15phr | 98.2                       | 37.1                    |
| LLDPE/Lignin 20phr | 105.6                      | 40                      |

The decrease in tensile strength and elongation at break is considered as a result of non-uniformly distributed lignin in LLDPE/lignin biocomposite which causes an agglomeration affecting its stress distribution [26]. The elongation at break of LLDPE/lignin biocomposites was drastically decreased compared to LLDPE. This was probably caused by the presence of lignin in LLDPE/lignin biocomposites which results in fragility due to lack of interface adhesion. This lack of interface adhesion can be attributed to reduce the flexibility of LLDPE/lignin biocomposites. Moreover, the presence of lignin also increased the brittleness and affected the viscoelastic property of LLDPE/Lignin biocomposites. The hydrophilic characteristic nature of lignin results in incompatibility of lignin with LLDPE hydrophobic characteristic and tendency to form aggregates. This lignin’s hydrophilic characteristic is also the cause that lignin is not tough to humidity which leads to high water absorption. Therefore, it causes the poor tensile properties of LLDPE/lignin biocomposites. In this case, a chemical modification is needed to improve lignin hydrophobic and decrease moisture absorption, leading to the enhancement of tensile properties of the composites [52]. Tensile strength and elongation at break shows decreasing tendency as the composition of lignin addition is increased. However, when the composition of lignin were added at 15 phr (LLDPE/lignin 15) and 20 phr (LLDPE/lignin 20), tensile strength and elongation at break increased in comparison with the addition of lignin by 5 phr (LLDPE/lignin 5) and 10 phr (LLDPE/lignin 15), but still lower than LLDPE. This is probably due to the lignin distribution in LLDPE/Lignin 15 and LLDPE/lignin 20 are more uniformly and less agglomerated compared to the lignin distribution in LLDPE/lignin 10, so that the tensile strength and elongation at break are increased.

3.4. Morphology

SEM micrographs of the fractured surface for LLDPE/lignin biocomposites films are shown in Figure 5. Figure 5(a), 5(b), 5(c), 5(d), and 5(e) show the SEM image of LLDPE, LLDPE/lignin 5, LLDPE/lignin 10, LLDPE/lignin 15, and LLDPE/lignin 20, respectively. Figure 5(a) shows relatively smooth and ductile surface of LLDPE. Figure 5(b) shows good lignin dispersion in the composite
surface. However SEM micrographs of agglomerated surface in the LLDPE/lignin biocomposite was shown in Figure 5(c) – 5(e). The addition of lignin from 10, 15 and 20 phr caused agglomeration of lignin. The agglomeration shown in the surface structure of bio-composites was caused by poor interfacial adhesion occurred between two phases [53]. Lignin was distributed non-uniformly in LLDPE/lignin biocomposites. LLDPE/lignin 15 (Figure 5d) and LLDPE/lignin 20 (Figure 5e) showed smoother surface than LLDPE/lignin 10 (Figure 5c). It was also probably the reason why the tensile strength and elongation at break LLDPE/lignin 15 and LLDPE/lignin 20 was higher than LLDPE/lignin 10. The addition of lignin into LLDPE made the surface structure of the resulted LLDPE/lignin biocomposites become rougher. This rough surface also possibly initiated faster biodegradation. The agglomeration can result in the lack of interface adhesion, thus, leads in a poor distribution of stress when pressured. Furthermore, it will result in the degradation of tensile strength and elongation at break. This phenomena was reported that the interfacial interaction between filler and polymer matrix in the composite affect the mechanical properties of the composite [54].

Figure 5. SEM micrograph of (a) LLDPE; (b) LLDPE/Lignin 5 phr; (c) LLDPE/Lignin 10phr; (d)LLDPE/Lignin 15 phr and (e) LLDPE/Lignin 20 phr
3.5. Biodegradability

The effect during degradation process greatly depends on hydrophilicity or hydrophobicity and particle dispersion. Moreover, the delay in biodegradability is caused by the increase in barrier properties of the material which can prevent water diffusion through the bulk [55]. The effect of lignin addition to the biodegradability of LLDPE/Lignin biocomposites is studied using ASTM G21-70. The results are shown in Table 3.

During 68 days of observation, the degradation rate of LDPE/Lignin 5, LLDPE/lignin 10, LLDPE/lignin 15 and LLDPE/lignin 20 are 0.1916, 0.2325, 0.3261 and 0.2864%, respectively. These LLDPE/lignin biocomposite degradations were associated with the presence of lignin which has many hydrophilic functional groups that promote biodegradation. The more lignin were added into LLDPE/lignin biocomposites, the more the materials were biodegraded. This is because as the number of lignin added increases, the biocomposites become more hydrophilic, and therefore, the material become more biodegradable.

| Table 3. Biodegradability level of LLDPE/Lignin biocomposite |
|-------------------------------------------------------------|
|                | Mass (gram) | Biodegradation (%) |
|                | Initial     | Final      |                |
| LLDPE/Lignin 5phr | 0.3392      | 0.3386    | 0.1916         |
| LLDPE/Lignin 10phr | 0.3227      | 0.3219    | 0.2325         |
| LLDPE/Lignin 15phr | 0.2760      | 0.2751    | 0.3261         |
| LLDPE/Lignin 20phr | 0.3318      | 0.3308    | 0.2864         |

However, at the lignin composition LDPE/lignin 20, the biodegradation result is lower than LLDPE/lignin 15. It was allegedly because of lignin has structural complexity and high molecular weight so the optimal biodegradability of fungi especially aspergillus niger to degrade the lignin is not more than 15 phr (LDPE/lignin 15). For lignin degradation requires specific enzyme, possibility some of the enzyme from aspergillus niger is non-specific for lignin so its ability to degrade lignin is not optimal for the large composition [56].

4. Conclusion

The FTIR spectrum of all LLDPE/lignin biocomposite showed similar absorption peak with lignin and also show absorption peaks at wavenumber of 1730 cm\(^{-1}\) related to C=O from the compatibilizer. It was indicated that absorption peak of LLDPE/lignin biocomposite is mixture between absorption peak of LLDPE and lignin and shows that the LLDPE/lignin biocomposites was successfully manufactured. The composition of lignin added to LLDPE affects the color of LLDPE/lignin biocomposites produced. The degradation thermal stability of LLDPE/lignin biocomposites is allegedly due to the
empty space in the LLDPE/lignin biocomposites which is filled with oxygen or air trapped. Subsequently, it will initiate the degradation process resulting in lower thermal stability. However, the thermal stability LLDPE/lignin biocomposites is increased at temperature over 460°C compared to LLDPE. The increase in thermal stability of LLDPE/lignin is due to the appearance of complex phenylpropanoid unit containing aromatic phenyl groups from lignin. In addition, the presence of multiple hydroxyl groups also contribute in the improvement of the stability of aromatic structures within the structure of lignin so that it will increase the mass of the remaining. The addition of lignin into LLDPE made the surface structure of the resulted LLDPE/lignin biocomposites become rougher and distributed non-uniformly in LLDPE/lignin biocomposites. This rough surface also possibly initiated faster biodegradation. The agglomeration can result in the lack of interface adhesion, thus, leads in a poor distribution of stress when pressurized. Furthermore, it will result in the degradation of tensile strength and elongation at break. The addition of lignin results in enhancement of biodegradability properties of LLDPE/lignin biocomposites. These LLDPE/lignin biocomposite degradations were associated with the presence of lignin which has many hydrophilic functional groups that promote biodegradation.

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