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Tensile strength of wood polylactic acid composite: A meta-analysis

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It is worth mentioning that polylactic acid (PLA) is extracted from plants and it can be considered a renewable resource. The sustainable development of resources can be achieved by turning PLA and wood production into wood plastic composite (WPC). In this study, the mechanical properties of WPC were compared in a meta-analysis that focused on WPC made with PLA because the tensile strength (TS) of WPC compared with PLA was unclear. We assessed changes in the mechanical properties of PLA and wood used to make WPC by identifying 1919 peer-reviewed manuscripts, of which 15 articles were included in this analysis. We found that adding 10%–50% wood flour reduced the TS, breaking elongation, and impact strength of WPC. This did not affect the bending modulus. More work is required to solve the compatibility issues between wood fiber and plastics as well as to better understand the degradability of PLA-WPC. Additionally, the cost reduction for WPC synthesis must be addressed.

Keywords: Meta-analysis, Polylactic acid, Tensile strength, Wood, Wood plastic composite.

Introduction

Wood plastic composite (WPC) is a composite material made of waste wood and plastics [1]. WPC is simple to process, has suitable mechanical properties, is water-resistant, and it can be shaped in various ways [2-4]. WPC products have been continuously improved so that they are stable wood substitutes. As ecological protection awareness has increased and attention has been paid to sustainable resources, biodegradable WPC has been used for industrial production [5]. Currently, biodegradable macromolecule materials such as polylactic acid (PLA), and polybutylene succinate (PBS) have been successfully commercialized [6-8]. PLA has high strength and rigidity, and its tensile strength (TS) is greater than that of other biodegradable plastics. However, PLA has poor toughness and ductility and it is hard and brittle at room temperature [9]. PLA is also extracted from plants and it can be considered a renewable resource. Sustainable resource development can be achieved by turning PLA and wood into WPC.

Tensile strength is an important index for measuring the mechanical properties of WPC [10]. Some researchers have suggested that the TS of WPC is less than that of PLA, but other researchers have suggested the opposite [10-12]. Thus, this analysis was undertaken to determine the changes in the TS of WPC (that was made from PLA). We also studied some related mechanical properties and compared the differences between WPC and PLA.

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Methods

Database and data extraction

Our meta-analysis was conducted to assess how combining PLA and wood to make WPC affected the TS. Published literature from 1980 to January 2019 was searched from Science Direct, Springer, Web of Science, Wiley, and Ovid Technologies with the key words: 'wood plastic composite', 'wood composite', 'wood biocomposites', 'wood flour composite', 'polylactic acid', 'PLA', and 'tensile strength'. We identified 1919 articles that we screened for inclusion in the meta-analysis according to the criteria listed in Table 1.

Data analysis

In this meta-analysis, we focused on the percentage of wood. Thus, we separated the data by 10%, 20%, 30%, 40%, and 50% for each study. The equation for

Table 1. Inclusion and exclusion criteria

Inclusion	Exclusion
Wood included	Wood not used
English language	Non-English language
Control group included pure PLA; wood mix treatments and controls were handled the same way	Either no control group or different processes were used
TS data included	No TS data
Original research	Review

the average TS for each dataset was calculated as follows:

$$\overline{TS}=\sum_{i=1}^{n}\left(\frac{WPC_{TS}}{PLA_{TS}}\right)\times\frac{1}{n}\times 100\%$$

where PLA_{TS} is the pure PLA material TS, as a control group. WPC_{TS} is the WPC material TS with every dataset. The standard errors (SE) were calculated with the following equation

$$SE_{TS}=\frac{\sqrt{\sum_{i=1}^{n}\left[\left(\frac{WPC_{TS}}{PLA_{TS}}\right)_i-\overline{TS}\right]^2}}{n}$$

The similar breaking elongation and impact strength were calculated in the same way.

The equation of the average tensile modulus (TM) increase percentage for each dataset was calculated as follows:

$$\overline{TM}=\sum_{i=1}^{n}\left(\frac{WPC_{TM}}{PLA_{TM}}-1\right)\times\frac{1}{n}\times 100\%$$

where PLA_{TM} is the pure PLA material TM, as a control group. WPC_{TM} is the WPC material TM with every dataset. The standard errors (SE) of the TM were calculated with the following equation

$$SE_{TM}=\frac{\sqrt{\sum_{i=1}^{n}\left[\left(\frac{WPC_{TM}}{PLA_{TM}}\right)_i-\overline{TM}\right]^2}}{n}$$

The similar bending modulus was calculated in the same way.

The heterogeneity was determined using the Higgins statistic, a p-value, and an I^2 statistic [13]. A categorical random-effects model was adopted using Review Manager, Version 5.3 (Copenhagen: Nordic Cochrane Centre, Cochrane Collaboration).

Results

We retrieved 1919 articles and 15 articles were included (Fig. 1 and Table 2). From these 15 articles, we retrieved 33 TS datasets. Fig. 2(a) shows that with WPC made with PLA, mixing 10~50% wood fibers reduced the TS. The WPC TS character reached only 64% pure PLA. Fig. 2(b) shows WPC mixed with 10%, 20%, 30%, and 50% wood fibers. All of the mixtures showed reduced breaking elongation. Overall, the WPC materials were able to stretch only 47% as far as the pure PLA materials before breaking. Fig. 2(c) shows that WPC with 10~50% wood fibers could increase the tensile modulus to 140% of pure PLA. In addition, mixed wood fibers did not affect

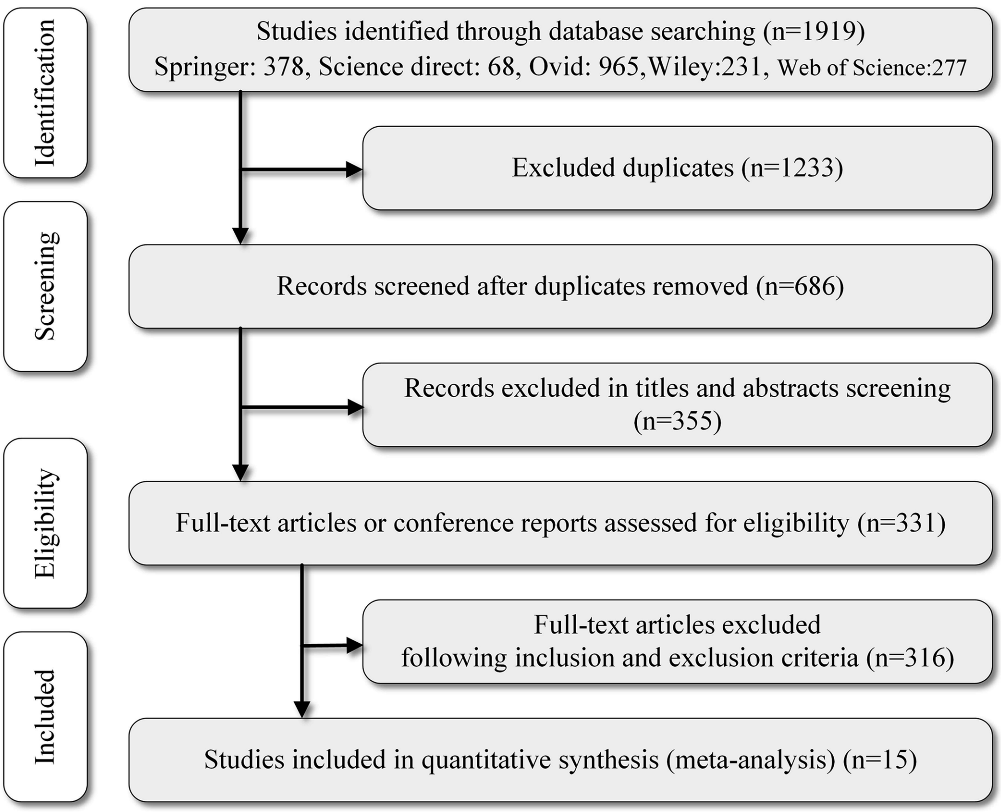

Fig. 1. Summary of the study selection process.

Table 2. Characteristics of included studies

	Study	Year	Wood species	Wood flour diameter	Processing	WF treatment
1	Azwar[36]	2012	Not mentioned	Not mentioned	Solution casting	Untreated
2	Azwar[5]	2012	Not mentioned	Not mentioned	Solution casting	Untreated
3	Febrianto[32]	2006	Not mentioned	Not mentioned	Compression molding	Maleic anhydride
4	Tisserat[37]	2013	Paulownia	3 mm	Extrusion	Untreated
5	Asadi[11]	2018	Not mentioned	Not mentioned	Compression molding	Untreated
6	Yang[10]	2019	Eulaliopsis binata	Not mentioned	Extrusion	NaOH
7	Petchwattana Covavisaruch [12]	2014	Rubber	Not mentioned	Injection molding	Untreated
8	Georgiopoulos[44]	2015	Not mentioned	70–150, 300, 200–500 μm	Compression molding	Untreated
9	Petinakis[34]	2009	Not mentioned	30 mm	Extrusion	Untreated
10	Altun[33]	2012	pine	Not mentioned	Injection molding	NaOH
11	Gregorova[45]	2011	European beech	100 μm	Compression molding	Untreated
12	Tsou[14]	2015	poplar	Not mentioned	Compression molding	NaOH
13	Formela[35]	2016	Rubber	Not mentioned	Compression molding	Untreated
14	Dong[46]	2018	Not mentioned	1.75 mm	3D printing	Untreated
15	González[16]	2018	Not mentioned	1.2 mm	Rotational molding	Untreated

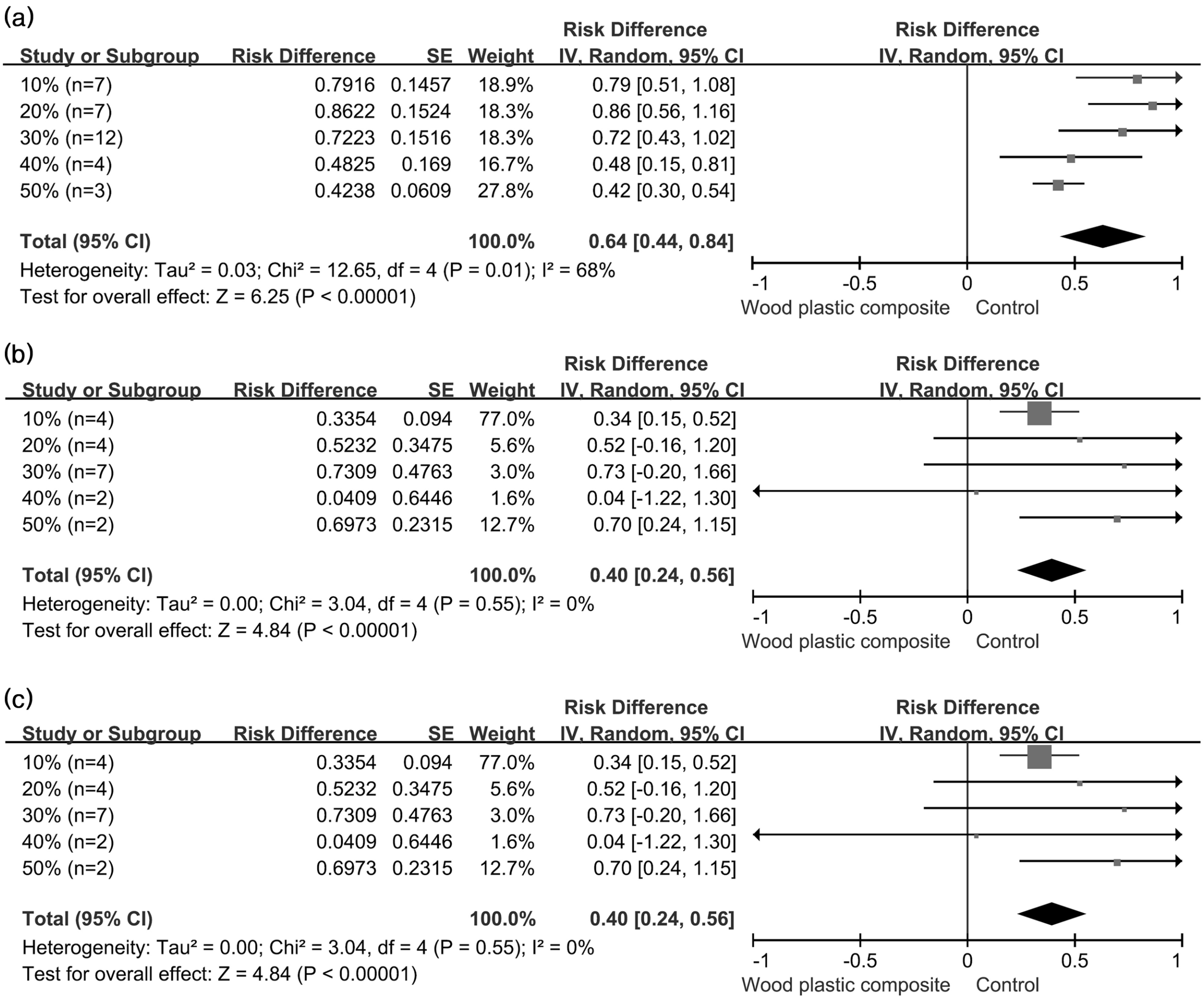

Fig. 2. Forest plot of the meta-analysis. (A) wood fiber mixing effect on TS change for different datasets, (B) effect on WPC change for the breaking elongation, and (C) effect on WPC tensile modulus change. CI = 95% confidence interval.

the bending modulus (Fig. 3(a)). WPC could reach 74% of the impact strength of pure PLA (Fig. 3(b)).

Discussion

The most important factor affecting the mechanical

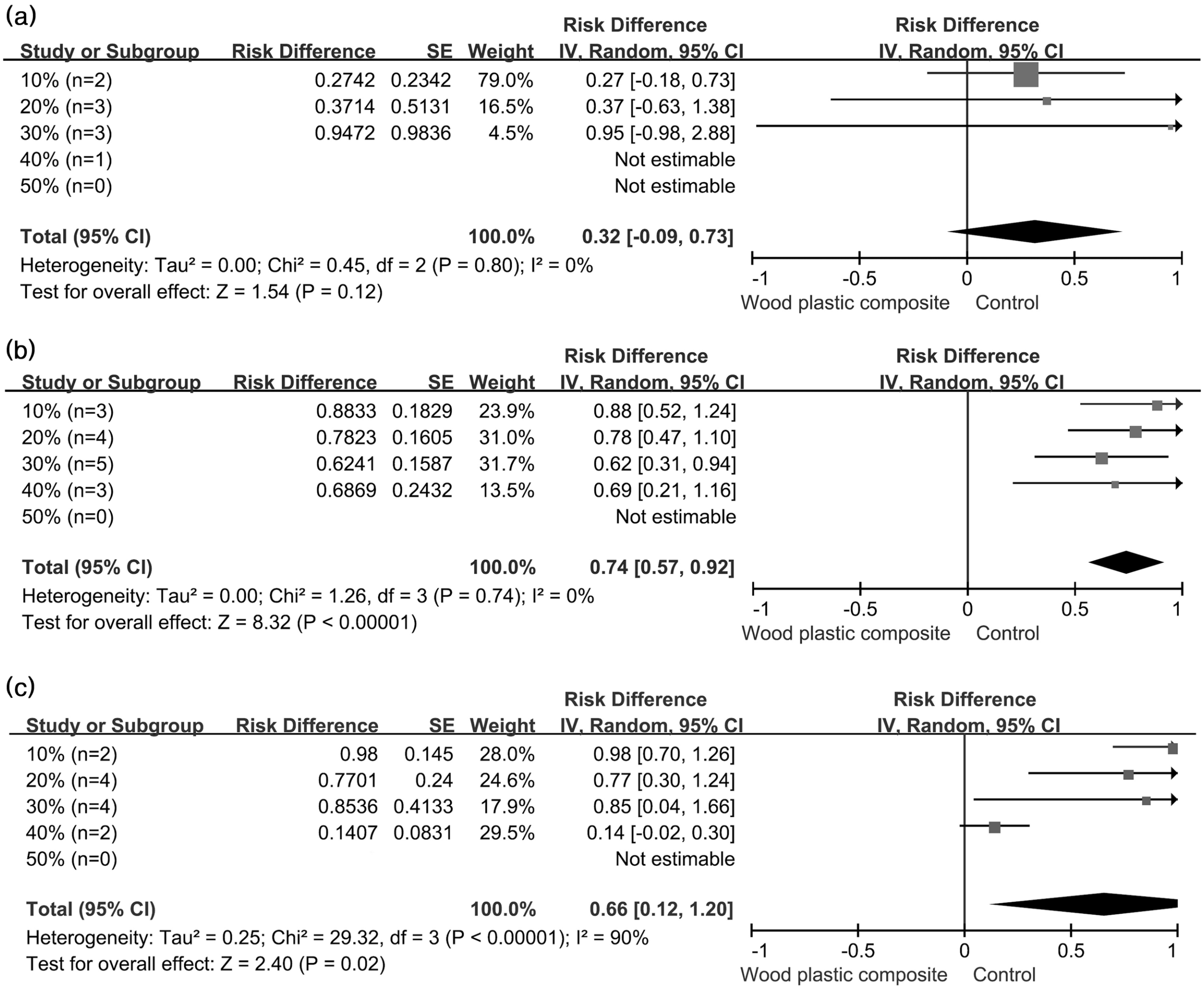

Fig. 3. Forest plot of the meta-analysis. (A) wood fiber mixing effect on the bending modulus change for different datasets, (B) effect on WPC change impact strength. CI = 95% confidence interval.

properties of WPC is the proportion of wood flour added to a mixture [14]. We found that adding 10%–50% wood flour reduced the TS, breaking elongation, and impact strength. WPC offers a way to use waste wood, reduce resource waste, and reduce the cost of plastic products [15]. The TS along a wood grain direction is the largest of all wood strengths. Because WPC contains wood flour, its TS is less than that of plastics [16].

Cellulose, hemicellulose, and lignin are the main components of wood flour [17]. Wood flour cellulose has a large number of hydroxyl groups [18]. Chemical and physical methods can be used to pretreat or modify lignocellulosic fibers, which can reduce fiber surface smoothness or alter fibers to form oil-affinity non-polar groups and increase their fluidity, reduce repulsion between fibers and hydrophobic polymers, and improve the interfacial compatibility between the two material phases [19]. At present, heat, steam explosion [20], alkali [21], and etherification [22] treatments and grafting modifications are more common approaches for wood fiber [20-23]. Studies showed that wood fiber and PLA could be easily distinguished for each sample section due to the poor compatibility between wood flour fiber and plastic.

Hemicellulose has a low molecular weight and poor stability, which reduces the strength of WPC [24]. Hemicellulose in wood flour can be removed with hot water or alkali treatments and it can be degraded by high temperature or steam explosion treatments [24]. The mechanical properties, dimensional stability, and interfacial compatibility of WPC prepared from wood flour with hemicellulose removal were improved, and water absorption decreased [25].

Lignin has a three-dimensional network structure and it is hydrophobic [26]. The poor interfacial bonding of lignin-filled polypropylene composites results in poor mechanical properties of WPC compared with pure polypropylene [27]. When lignin is added to WPC as a coupling agent, the TS and modulus of the composites increase and the water absorption and swelling of the water absorption thickness decrease [28]. Additionally, the thermal stability increases, but it is not conducive to the aging resistance of the composites [29].

Tree wood flour has different textures as well as variable cellulose, hemicellulose, lignin, and extract content [30]. The degree of uniformity of the dispersion in matrix plastics varies during polymerization. Wood flour drying is uneven and moisture remains, which influences the volume of wood flour in WPC with the same components [31]. Thus, properties vary for WPC prepared from different wood flours. Our study evaluated different types of wood. A lack of heterogeneity was not found upon the calculation of the breaking elongation, tensile modulus, bending modulus, or impact strength.

WPC is processed by mixing, and it is formed with extrusion, pressing, and injection molding [10, 32, 33]. Extrusion can be continuous and it offers uniformity. Compared with other methods, extrusion is a low-consumption and high-output production process, suitable for the production of various profiles and sheets. WPC processing is widely used in industrial production [34]. Compression molding is one of the oldest methods of polymer processing and it involves adding premix into a mold and pressing the material to melt it until it has a viscous flow. Then the material is pressed into WPC products [35]. In our study, different WPC mixing processes were combined and calculated in a unified way.

WPC is brittle and when it is impacted by external forces, fractures often occur. The interface compatibility between wood flour and matrix plastics is poor, and it is difficult to form stable chemical bonds between them; usually only physical bonding occurs [36]. Therefore, when a large amount of wood fiber is added, wood fiber produces stress concentration points in WPC, which are more likely to form cracks that propagate. This hinders further the polymerization of plastics in the melting process, making the plastic chain smaller [37]. For these reasons, WPCs are prone to brittle fractures at the joints of the wood flour fiber and plastic matrix when impacted by external forces, which results in poor toughness for the WPC [9]. To improve the toughness of WPC and expand its application and service life, the following methods are generally used: (1) improving the strengthof the plastic matrix, (2) adding a toughening agent, (3) optimizing the properties of wood fiber, such as addition, particle size, and dispersion, and (4) increasing the length-diameter ratio of the fillers [38].

Lactic acid is obtained by the fermentation of starch that is extracted from renewable resources such as corn and potatoes and is polymerized into PLA [8, 39]. PLA is biodegradable and it can be completely decomposed and combined in soil or water under the action of microorganisms, water, acid, and alkali in a day. This then becomes the starting material for starch under photosynthesis. PLA is not a pollutant. It is extracted from plants and it can be considered a renewable resource [39]. However, PLA has some shortcomings. First, PLA contains a large number of non-polar hydrophobic carboxyl and ester bonds, which leads to poor compatibility between PLA and most polar substances containing hydrophilic hydroxyl groups. Because PLA is a linear polymer, its thermal deformation temperature is low, its impact resistance is poor, and its appearance is hard and brittle [40]. That is why we have focused our research on PLA.

Recently, PLA has been modified [2] with blending, copolymerization modification, and nano-composite modification [41, 42]. Due to the complex production process and high investment cost of copolymerization modification, this type of toughening is still in the research stage, and few commercialized copolymerization modification products are available [42]. Toughening with a controlled molding process is suitable only for the production of specific products and not for the modification of conventional resin raw materials. Blending modification can be used because of its simple production process and easy controllability [41].

Limitations

Due to the limited published data, we assessed the proportion of wood flour added to WPC. The mechanical properties of WPC are affected by the different sizes of wood fiber, tree species, molding processes, and compatibility treatments of wood fiber [35, 37]. We did not address these in this meta-analysis; this is one limitation of our work.

Conclusion

There are unsolved problems with the dispersion and compatibility of wood flour in plastics. Wood flour self-polymerization often occurs, resulting in wood flour particles in the plastic matrix resin that are not uniformly dispersed [32]. Therefore, to produce WPC with good properties, compatibility issues must be solved.

The mechanical properties of WPC are weaker than the mechanical properties of solid wood, so plastics are mixed with wood particles to strengthen the material. However, these products are weaker than plastics [10]. Compared with pure PLA, the TS, breaking elongation, tensile modulus, bending modulus, and impact strength of WPC did not change, even though the value was measured twice. For this reason, the current focus with respect to WPC is on reducing manufacturing costs. PLA and wood fibers are derived from the environment, and as such, they are biodegradable. There is a raw material mixing step in the WPC production process. If self-healing material is added [43], WPCs may be used in a wider range of fields.

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References

1. X. Lin, Z. Zhang, Z. Zhang, J. Sun, Q. Wang, and C.U. Pittman, Waste Manag. 79 (2018) 38-47.
2. X. Gao, L. Lin, J. Pang, F. Chen, and Q. Li, Carbohydr Polym. 207 (2019) 343-351.
3. T. Ozdemir, and F. Mengeloglu, Int. J. Mol. Sci. 9[12] (2008) 2559-2569.
4. O. Das, A. K. Sarmah, and D. Bhattacharyya, Waste Manag. 38 (2015) 132-40.
5. E. Azwar, B. Yin, and M. Hakkarainen, J. Chem. Technol. Biot. 88 (2013) 897-903.
6. E. Azwar, B. Yin, and M. Hakkarainen, J. Chem. Technol. Biot. 88[5] (2013) 897-903.
7. X. Qi, J.G. Liu, and L.F. Huang, Zhongguo Xiu Fu Chong Jian Wai Ke Za Zhi, 15[4] (2001) 202-205.
8. A.K. Urbanek, W. Rymowicz, M.C. Strzelecki, W. Kociuba, L. Franczak, and A.M. Mironczuk, AMB Express. 7[1] (2017) 148.
9. L. Quiles-Carrillo, N. Montanes, F. Pineiro, A. Jorda-Vilaplana, and S. Torres-Giner, Materials (Basel) 11[11] (2018) 2138.
10. Y. Yang, L. Haurie, J. Wen, S. Zhang, A. Ollivier, and D. Wang, Ind. Crop. Prod. 130 (2019) 301-309.
11. M. Asadi, B. Bazyar, A. H. Hemmasi, I. Ghsemi, and M. Talaeipoor, Sci. J. Wood Technol. 69[2] (2018) 127-134.
12. N. Petchwattana, and S. Covavisaruch, J. Bionic. Eng. 11[4] (2014) 630-637.
13. M.L. de la Cruz, I. Conrado, A. Nault, A. Perez, L. Dominguez, and J. Alvarez, Res. Vet. Sci. 114 (2017) 86-94.
14. C.-Y. Tsou, C.-L. Wu, C.-H. Tsou, S.-H. Chiu, M.-C. Suen, and W.-S. Hung, Polym. Sci. Ser. B 57[5] (2015) 473-480.
15. P.F. Sommerhuber, J. Welling, and A. Krause, Waste Manag. 46 (2015) 76-85.
16. M. González, A. Perez Fonseca, E. Cisneros López, R. Manríquez-González, D. Ramírez-Arreola, D. Rodrigue, and J. Robledo-Ortíz, J. Polym. Environ. 27 (2018) 10-22.
17. Z.C. Pedri, L.M. Lozano, K.L. Hermann, C.V. Helm, R.M. Peralta, and L.B. Tavares, Braz. J. Biol. 75[4] (2015) 940-947.
18. X. Zhang, X. Wu, H. Haryono, and K. Xia, Carbohydr Polym. 113 (2014) 46-52.
19. B. Arslan, K. Egerton, X. Zhang, and N.I. Abu-Lail, Langmuir 33[27] (2017) 6857-6868.
20. T. Eom, S. Chaiprapat, and B. Charnnok, J. Environ. Manage. 235 (2019) 231-239.
21. M. Broda, and C.M. Popescu, Spectrochim Acta A Mol. Biomol. Spectrosc. 209 (2019) 280-287.
22. J. Chen, F. Lu, X. Si, X. Nie, J. Chen, R. Lu, and J. Xu, Chem. Sus. Chem. 9[23] (2016) 3353-3360.
23. H.J. Hong, H. Yu, M. Park, and H.S. Jeong, Carbohydr Polym. 210 (2019) 167-174.
24. B.T. Martinez, A.T. Quintana, Y.T. Cambas, and F.O. Roque, Neotrop. Entomol. 48[4] (2019) 527-537.
25. J. Olsson, V. Novy, F. Nielsen, O. Wallberg, and M. Galbe, Biotechnol Biofuels. 12 (2019) 1.
26. F. Zikeli, V. Vinciguerra, A. D'Annibale, D. Capitani, M. Romagnoli, and G. Scarascia Mugnozza, Nanomaterials (Basel), 9[2] (2019) 281.
27. G. Cicala, C. Tosto, A. Latteri, A. D. La Rosa, I. Blanco, A. Elsabbagh, P. Russo, and G. Ziegmann, Materials (Basel) 10[9] (2017) 998.
28. L. Lagerquist, A. Pranovich, I. Sumerskii, S. von Schoultz, L. Vahasalo, S. Willfor, and P. Eklund, Molecules, 24[2] (2019) 335.
29. J. Reyes-Rivera, G. Canche-Escamilla, M. Soto-Hernandez, and T. Terrazas, PLoS One 10[4] (2015) e0123919.
30. B.D. Kasseney, T. Deng, and J. Mo, J. Econ. Entomol. 104[3] (2011) 862-867.
31. J. Bossu, J. Beauchene, Y. Estevez, C. Duplais, and B. Clair, PLoS One, 11[3] (2016) e0150777.
32. F., Febrianto, M., Yoshioka, Y., Nagai, P.M.D., Tahir, W., Syafii and N., Shiraishi, J. Biol. Sci. 6 (2006) 555-563.
33. Y. Altun, M. Doğan, and E. Bayramlı, J. Polym. Environ. 21[3] (2013) 850-856.
34. E. Petinakis, L. Yu, G. Edward, K. Dean, H. Liu, and A.D. Scully, J. Polym. Environ. 17[2] (2009) 83-94.
35. K. Formela, A. Hejna, Ł. Piszczyk, M.R. Saeb, and X. Colom, Cellulose 23[5] (2016) 3157-3175.
36. E. Azwar, E. Vuorinen, and M. Hakkarainen, Polym. Degrad. Stabil. 97[3] (2012) 281-287.
37. B. Tisserat, N. Joshee, A.K. Mahapatra, G.W. Selling, and V.L. Finkenstadt, Ind. Crop. Prod. 44 (2013) 88-96.
38. A. Winter, N. Mundigler, J. Holzweber, S. Veigel, U. Muller, A. Kovalcik, and W. Gindl-Altmutter, Philos. Trans. A Math. Phys. Eng. Sci. 376[2112] (2018) 20170046.
39. R. Hashide, K. Yoshida, Y. Hasebe, M. Seno, S. Takahashi, K. Sato, and J. Anzai, J. Nanosci Nanotechnol 14[4] (2014) 3100-3105.
40. Y. Zuo, J. Gu, L. Yang, Z. Qiao, H. Tan, and Y. Zhang, Int. J. Biol. Macromol. 64 (2014) 174-180.
41. D. Li, Y. Jiang, S. Lv, X. Liu, J. Gu, Q. Chen, and Y. Zhang, PLoS One 13[3] (2018) e0193520.
42. L. Gritsch, G. Conoscenti, V. La Carrubba, P. Nooeaid, and A.R. Boccaccini, Mater. Sci. Eng. C Mater. Biol. Appl. 94 (2019) 1083-1101.
43. M.W. Lee, S.S. Yoon, and A.L. Yarin, ACS Appl. Mater. Interfaces 9[20] (2017) 17449-17455.
44. P. Georgiopoulos, E. Kontou, and A. Christopoulos, Composites Part B: Engineering 80 (2015) 134-144.
45. A. Gregorova, V. Sedlarik, M. Pastorek, H. Jachandra, and F. Stelzer, J. Polym. Environ. 19[2] (2011) 372-381.
46. Y. Dong, J. Milentis, and A. Pramanik, Adv. Manuf. 6[1] (2018) 71-82.