Current Progress in Biopolymer-Based Bionanocomposites and Hybrid Materials

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Current Progress in Biopolymer-Based Bionanocomposites and Hybrid Materials is a newly opened Special Issue of Polymers, which aims to publish original and review papers on the new scientific and applied research and make boundless contributions to the findings and understanding of the reinforcing effects of various synthetic and natural fibres on the performance of biopolymer composites. This Special Issue also covers the hybrid nanofibre-reinforced biopolymer nanocomposites’ fundamentals, characterisation, and applications.

In recent years, the development of biopolymers based on constituents obtained from natural resources has been gaining much attention [1,2]. The exploitation of biopolymers to engineer advanced bionanocomposites and hybrid materials is the focus of increasing scientific activity, explained by the growing environmental concerns and the interest in the novel features and multiple functionalities of these macromolecules.

Today, nanomaterial-reinforced polymers are used in several applications including in packaging [2–4]; electronic, electrical, structural, and energy storage [5]; in automotives [6]; in filter, coating, and bone tissue engineering, and in drug delivery [7], and more. The continuous development and appearance on the market of new high-performance reinforcing nanomaterials in polymer composites have constituted a strong challenge for researchers to design and adapt new functional nano-composites for several applications. The term bionanocomposites was introduced several years ago to express an emerging class of bionano- and bionanohybrid materials, resulting from the reinforcement of biopolymers, such as proteins (gelatin, casein, soy, and gluten), polysaccharides (cellulose, starch, chitosan, pectin, alginate, carrageenan, and glycopenc), lipids (cutin), and nucleic acids with inorganic or organic solids at the nanoscale [8–13]. Such organic fractions comprise nanocrystalline cellulose [14–16], nanofibrillated cellulose [17,18] (Figure 1), bacterial nanocellulose [19], and lignin nanoparticles [20], whereas inorganic fractions consist of finely divided solids, spanning from clays to phosphates or carbonates, whose origins can be either synthetic or natural.

As will become increasingly clear for the reader throughout the collection of authoritative research and reviews in this Special Issue, the relevance of coupling biopolymers with organic and inorganic fillers, through innovative architectures, is twofold. First, it contradicts the idea that biopolymers are either eco-friendly or high-performance. Second, it demonstrates how the properties resulting from these biopolymers are highly significant in applications such as food packaging, water treatment, gas-diffusion barriers, electronic devices, agriculture, sensing devices, flame retardancy, automotive parts, adhesives, regenerative medicine, tissue engineering, and drug delivery [21].
In this Special Issue, we aim to capture the cutting edge of the state of the art in research pertaining to biopolymer-based bionanocomposites and hybrid materials and their advanced applications. Contributions to the processing of biopolymers and bionanocomposites, the use of diverse biopolymer sources such as polysaccharides, the reinforcement of nanosized materials with biopolymers, and applications of these biopolymers, bionanocomposites, and biohybrid materials will constitute the backbone of this Special Issue.

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**References**

1. Tarique, J.; Sapuan, S.M.; Khalina, A.; Ilyas, R.A.; Zainudin, E.S. Thermal, flammability, and antimicrobial properties of arrowroot (Maranta arundinacea) fiber reinforced arrowroot starch biopolymer composites for food packaging applications. *Int. J. Biol. Macromol.* 2022, 213, 1–10. [CrossRef] [PubMed]

2. Nazrin, A.; Sapuan, S.M.; Zuhri, M.Y.M.; Tawakkal, I.S.M.A.; Ilyas, R.A. Flammability and physical stability of sugar palm crystalline nanocellulose reinforced thermoplastic sugar palm starch/poly (lactic acid) blend bionanocomposites. *Nanotechnol. Rev.* 2022, 11, 86–95. [CrossRef]

3. Rozilah, A.; Jaafar, C.N.A.; Sapuan, S.M.; Zainol, I.; Ilyas, R.A. The Effects of Silver Nanoparticles Compositions on the Mechanical, Physiochemical, Antibacterial, and Morphology Properties of Sugar Palm Starch Biocomposites for Antibacterial Coating. *Polymers* 2020, 12, 2605. [CrossRef] [PubMed]

4. Alias, A.H.; Norizan, M.N.; Sabaruddin, F.A.; Asyraf, M.R.M.; Norrrahim, M.N.F.; Ilyas, A.R.; Kuzmin, A.M.; Rayung, M.; Shazleen, S.S.; Nazrin, A.; et al. Hybridization of MMT/Lignocellulosic Fiber Reinforced Polymer Nanocomposites for Structural Applications: A Review. *Coatings* 2021, 11, 1355. [CrossRef]

5. Nurazzi, N.M.; Sabaruddin, F.A.; Harussani, M.M.; Kamarudin, S.H.; Rayung, M.; Asyraf, M.R.M.; Aisyah, H.A.; Norrrahim, M.N.F.; Ilyas, R.A.; Abdullah, N.; et al. Mechanical Performance and Applications of CNTs Reinforced Polymer Composites—A Review. *Nanomaterials* 2021, 11, 2186. [CrossRef]

6. Nurazzi, N.M.; Asyraf, M.R.M.; Rayung, M.; Norrrahim, M.N.F.; Shazleen, S.S.; Rani, M.S.A.; Shafi, A.R.; Aisyah, H.A.; Radzi, M.H.M.; Sabaruddin, F.A.; et al. Thermogravimetric Analysis Properties of Cellulosic Natural Fiber Polymer Composites: A Review on Influence of Chemical Treatments. *Polymers* 2021, 13, 2710. [CrossRef]

7. Sharma, S.; Sudhakara, P.; Singh, J.; Ilyas, R.A.; Asyraf, M.R.M.; Razman, M.R. Critical Review of Biodegradable and Bioactive Polymer Composites for Bone Tissue Engineering and Drug Delivery Applications. *Polymers* 2021, 13, 2623. [CrossRef]
8. Ilyas, R.A.; Zuhri, M.Y.M.; Aisyah, H.A.; Asyraf, M.R.M.; Hassan, S.A.; Zainudin, E.S.; Sapuan, S.M.; Sharma, S.; Bangar, S.P.; Jumaidin, R.; et al. Natural Fiber-Reinforced Polylactic Acid, Polylactic Acid Blends and Their Composites for Advanced Applications. Polymers 2022, 14, 202. [CrossRef]

9. Norfarhana, A.S.; Ilyas, R.A.; Ngadi, N. A review of nanocellulose adsorptive membrane as multifunctional wastewater treatment. Carbohydr. Polym. 2022, 291, 119563. [CrossRef]

10. Ilyas, R.A.; Zuhri, M.Y.M.; Norrrahim, M.N.F; Misenan, M.S.M.; Jenol, M.A.; Samsudin, S.A.; Nurazzi, N.M.; Asyraf, M.R.M.; Supian, A.B.M.; Bangar, S.P.; et al. Natural Fiber-Reinforced Polycaprolactone Green and Hybrid Biocomposites for Various Advanced Applications. Polymers 2022, 14, 182. [CrossRef]

11. Ilyas, R.A.; Aisyah, H.A.; Nordin, A.H.; Ngadi, N.; Zuhri, M.Y.M.; Asyraf, M.R.M.; Sapuan, S.M.; Zainudin, E.S.; Sharma, S.; Abral, H.; et al. Natural Fiber-Reinforced Chitosan, Chitosan Blends and Their Nanocomposites for Various Advanced Applications. Polymers 2022, 14, 874. [CrossRef] [PubMed]

12. Nabilah Haris, N.I.; Hassan, M.Z.; Ilyas, R.A.; Suhot, M.A.; Sapuan, S.M.; Dolah, R.; Mohammad, R.; Asyraf, M.R.M. Dynamic mechanical properties of natural fiber reinforced hybrid polymer composites: A review. J. Mater. Res. Technol. 2022, 19, 167–182. [CrossRef]

13. Ilyas, R.A.; Sapuan, S.M.; Asyraf, M.R.M.; Dayana, D.A.Z.N.; Amelia, J.J.N.; Rani, M.S.A.; Norrrahim, M.N.F.; Nurazzi, N.M.; Aisyah, H.A.; Sharma, S.; et al. Polymer Composites Filled with Metal Derivatives: A Review of Flame Retardants. Polymers 2021, 13, 1701. [CrossRef] [PubMed]

14. Ilyas, R.A.; Sapuan, S.M.; Atikah, M.S.N.; Asyraf, M.R.M.; Rafiqah, S.A.; Aisyah, H.A.; Nurazzi, N.M.; Norrrahim, M.N.F. Effect of hydrolysis time on the morphological, physical, chemical, and thermal behavior of sugar palm nanocrystalline cellulose (Arenga pinnata (Wurmb.) Merr). Text. Res. J. 2021, 91, 152–167. [CrossRef]

15. Abral, H.; Ariksa, J.; Mahardika, M.; Handayani, D.; Aminah, I.; Sandrawati, N.; Pratama, A.B.; Fajri, N.; Sapuan, S.M.; Ilyas, R.A. Transparent and antimicrobial cellulose film from ginger nanofiber. Food Hydrocoll. 2020, 98, 105266. [CrossRef]

16. Sabaruddin, F.A.; Paridah, M.T.; Sapuan, S.M.; Ilyas, R.A.; Lee, S.H.; Abdan, K.; Mazlan, N.; Roseley, A.S.M.; Abdul Khalil, H.P.S. The effects of unbleached and bleached nanocellulose on the thermal and flammability of polypropylene-reinforced kenaf core hybrid polymer bionanocomposites. Polymers 2020, 13, 116. [CrossRef]

17. Ilyas, R.A.; Sapuan, S.M.; Ishak, M.R.; Zainudin, E.S. Sugar palm nanofibrillated cellulose (Arenga pinnata (Wurmb.) Merr): Effect of cycles on their yield, physic-chemical, morphological and thermal behavior. Int. J. Biol. Macromol. 2019, 123, 379–388. [CrossRef] [PubMed]

18. Syafri, E.; Sari, N.H.; Mahardika, M.; Amanda, P.; Ilyas, R.A. Isolation and characterization of cellulose nanofibers from Agave gigantea by chemical-mechanical treatment. Int. J. Biol. Macromol. 2022, 200, 25–33. [CrossRef]

19. Abral, H.; Chairani, M.K.; Rizki, M.D.; Mahardika, M.; Handayani, D.; Sugiartri, E.; Muslimin, A.N.; Sapuan, S.M.; Ilyas, R.A. Characterization of compressed bacterial cellulose nanopaper film after exposure to dry and humid conditions. J. Mater. Res. Technol. 2021, 11, 896–904. [CrossRef]

20. Trevisan, H.; Rezende, C.A. Pure, stable and highly antioxidant lignin nanoparticles from elephant grass. Ind. Crops Prod. 2020, 145, 112105. [CrossRef]

21. Mohd Nurazzi, N.; Asyraf, M.R.M.; Khalina, A.; Abdullah, N.; Sabaruddin, F.A.; Kamarudin, S.H.; Ahmad, S.; Mahat, A.M.; Lee, C.L.; Aisyah, H.A.; et al. Fabrication, Functionalization, and Application of Carbon Nanotube-Reinforced Polymer Composite: An Overview. Polymers 2021, 13, 1047. [CrossRef] [PubMed]
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