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Architectured Multiphase Polymeric Carriers with Microstructural Gradients: Synergistic Filler Effects for the Precision Delivery in Tuberous Plant Systems

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Abstract

In this paper, 50 papers were reviewed to analyse the design, techniques, and applications of polymer composite systems for delivering agrochemicals against major tuberous plant pathogens, including fungi, bacteria, and nematodes. Primary tuber plant pathogens affecting yield are studied, followed by a study of control strategies. This is followed by a study of the basic properties of polymer composites, including the significance of natural and synthetic polymers. Then, the study of fillers to control the release of agrochemicals, such as fungicides, bactericides, nematicides, and biocontrol agents, is conducted. Various formulation types and strategies, such as nanoparticles, hydrogels, and seed coatings, are presented. The major tuberous plant pathogens and limitations of conventional control methods were reviewed, and polymer-based composite systems for agrochemical release were discussed throughout the paper, with examples of polymer composite formulations for pathogen control. The paper also discusses about how spatial variations in microstructural gradients such as matrix porosity and filler density help agricultural delivery performance. The research strategy is such that the mapping of Research questions to their Quality Assessment attributes was done. Also, the mapping solutions were mapped along in tabular form. Additionally, for each research paper, the core technology and Research focus area were also mapped.

Keywords: Polymer composites, agrochemicals, fillers, plant pathogens

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INTRODUCTION

Tuberous plants such as Solanum tuberosum, Tapioca, and Ipomoea batatas are used as food in the global market. These are types of potatoes and cassava that are essential energy-giving carbohydrates fed to a large population. But its cultivation is a huge challenge for farmers each year due to attacks by pathogens such as fungi and bacteria, which can ruin the entire farm's yields. Synthetic agrochemicals were used to prevent tuberous plant pathogens, but too few products penetrate the target tissue because they are lost to environmental stressors. This lag tremendously raises prices and leads to biotic resource loss. Also, excess utilisation maximises resistance to pathogens in the long run. It then becomes difficult to disinfect the bio-composite leaf and other biotic structures, such as the tuberous crops. Some of the major limitations of traditional control methods for tuberous plant pathogens are shown in Table 1, given below. Also, its purpose in Bio-composite analysis has also been explicitly mentioned in the table. Systematic review of the common tuberous plant pathogen causing diseases are controlled.

Nutrient distribution, soil amendment, and disease control are among the agricultural uses of polymer composites, which are materials made of polymer matrices reinforced with functional additives. They are compatible with agrochemicals, biodegradables and have variable release kinetics.

Polymer Composite Types

- *Biodegradable polymers:* Due to their environmentally friendly degradation pattern, polylactic acid, polyhydroxyalkanoates, and chitosan are often used.
- *Nanocomposites:* The addition of nanoparticles such as graphene oxide, zinc oxide, or silver improves mechanical strength and antibacterial properties.
- *Smart polymers:* Stimulus-sensitive polymers, such as those responsive to temperature or pH, enable targeted release of active substances.

FUNDAMENTALS OF POLYMER-BASED COMPOSITE SYSTEMS FOR CONTROLLED RELEASE OF AGROCHEMICALS

Polymer Composite Systems in Agricultural Applications

Polymer composites enable the structuring of targeted agrochemical and pathogen delivery systems. A summary of Polymer-Based Composite Systems for Agrochemical Release is presented in Table 2.

Table 1. Major tuberous plant pathogens and limitations of conventional control methods.

Pathogen (type)	Disease caused	Conventional chemical controls	Challenges	Purpose in Bio-composite analysis
Phytophthora infestans (Oomycete)	Late Blight	Phenylamide and metalaxyl-M fungicides.	Rapid resistance, high spray frequency, and environmental persistence.	Identifies the total area of degradation vs. healthy material.
Ralstonia solanacearum (Bacterium)	Bacterial Wilt (Brown Rot)	Antibiotics (e.g., streptomycin) and soil fumigants	Limited efficacy, antibiotic resistance, and high soil toxicity.	Categorizes specific morphology (cracks, voids, erosion).
Alternaria solani (Fungus)	Early Blight	DMI and strobilurin fungicides.	Resistance development, potential phytotoxicity, and a non-specific mode of action.	Validates segmentation accuracy against raw organic textures.
Globodera rostochiensis / G. pallida (Nematode)	Potato Cyst Nematode	Highly toxic fumigants/nematicides (e.g., carbofuran).	Extreme toxicity to mammals, severe regulations, and soil health disruption.	Isolates individual cysts or eggs to quantify soil-borne infestation levels.
Potato virus Y (Potyvirus)	PVY (various strains)	Insecticides for aphid vectors.	Indirect control: vector resistance kills beneficial insects but doesn't stop the initial infection.	Detects subtle chlorotic changes and mosaic patterns in leaf tissue before necrosis.

Table 2. Summary of polymer-based composite systems for agrochemical release.

Strategy	Typical materials	Release mechanism	Target pathogen example	Benefit
Micro/Nano-Encapsulation	PLA, PCL, Chitosan	Diffusion, Polymer degradation	Phytophthora infestans	Protection from UV degradation, reduced application frequency
Stimuli-Responsive Hydrogels	Chitosan, Alginate, Polyacrylamide	Swelling controlled by pH, enzymes	Pectobacterium spp.	On-demand, site-specific release; high efficiency
Polymer-Clay Nanocomposites	PLA/MMT, PVA/Halloysite	Tortuous diffusion, desorption	Fusarium spp., R. solanacearum	Extended release profile, enhanced mechanical properties

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Disease Management Mechanisms

Three main mechanisms underlie the action of polymer composites:

- *Pathogen inactivation:* The disruption of pathogen membranes or metabolic pathways through the release of nanoparticles or botanical extracts.
- *Barrier formation:* To stop spore germination, barrier coatings are applied to tubers or plant surfaces.
- *Controlled release:* Delivering biopesticides, antibiotics, or antifungal agents to diseased areas over time.

Principles of Controlled Release

The release of the active ingredient from a polymer composite mostly happens via Diffusion process**,** Polymer Degradation and Stimuli-Responsive Release, such as pH changes. Delivering agro-chemicals is a challenging task. The main agenda is to control pathogen levels by maintaining AI concentration within the optimal range in target tissues, such as the leaf surface and rhizosphere. The release highly relies on the polymer matrix, such as hydrophilicity and degradation rate, the nature of the filler, the AI's characteristics, such as solubility and charge, and environmental conditions, such as pH, temperature, and microbial activity.

Polymeric Matrices

Polymers form the backbone of any composite delivery system. They can be broadly classified into:

- *Natural polymers:* Derived from biological sources, these polymers are often biodegradable and environmentally friendly. Examples are cellulose, glucose and other natural fibres.
- *Synthetic polymers:* These are usually man-made and exhibit greater resistance to environmental degradation than natural polymers. Their composition and properties are more robust. Examples include polycaprolactone, polyacrylamide, and polyvinyl alcohol.
- *Semisynthetic polymers:* These are mixtures of natural and synthetic fibres, making them semisynthetic. It has properties of both. Some derivatives, including carboxymethyl cellulose are mostly utilised.

Role of the Composite Filler

Fillers make polymer coatings more robust and resilient to damage by environment. It controls the gradual release of agrochemicals. Sometimes, it reacts to pH alterations around the affected plant, delaying the release.

Synthesis and Application Methods

Effective crop protection also needs controlled delivery methods. Unlike conventional carriers that often exhibit burst release and loss of payload, structured polymeric systems with gradients in microstructure allow sustained and predictable release behavior. Spatial differences in carrier structure influence diffusion properties. Synergistic fillers such as cellulose nanocrystals and nanoclays enhance the release control further by a combination of interfacial and physical effects. Quantitative study of porosity, filler dispersion and mass balance is increasingly important in the characterization of these systems to evaluate delivery performance.

The common synthesis techniques are represented in Table 3 as follows.

RESEARCH METHODOLOGY

The workflow of the Literature Review done in this paper is given in Figure 1 as below.

Research Questions (RQs)

The Research Questions that arise pertaining to the role of bio-polymer composite for the controlled release of agrochemicals are as below mentioned in Table 4.

Quality Assessment Questions (QAs)

The Quality Assessment Questions that arise based on the review done are given in Table 5 below

Mapping RQs with QAs

The mapping of RQs to QAs is complete, and a QA score is assigned based on the strength of the mapping. It is represented in Table 6 as follows:

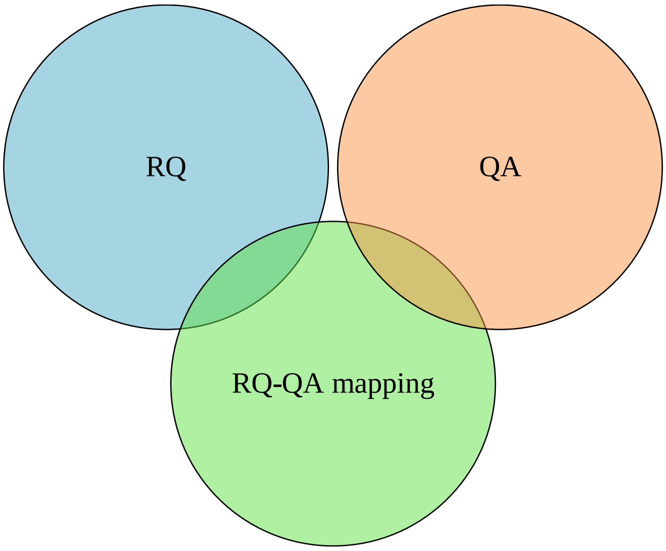

Figure 1. Research methodology workflow.

Table 3. Methods, examples of polymer composite formulations for tuberous plant pathogen control.

Formulation type	Matrix polymer(s)	Filler/AI combination	Target pathogen	Key advantage cited
Nanocomposite Film	Chitosan	Montmorillonite / Metalaxyl-M	*P. infestans*	Prolonged release, reduced resistance pressure.
Hydrogel Beads	Alginate	Copper Oxychloride	*A. solani*	Reduced phytotoxicity, improved rainfastness.
Seed Coating Gel	Carboxymethyl Cellulose	Streptomycin	*R. solanacearum*	Targeted root zone delivery, lower antibiotic use.
Soil-Applied Granules	Soluble Starch	Fosthiazate	*Globodera* spp.	Biodegradable, slow release, drastically lowered dosage.
Nanoparticles	Chitosan	*T. harzianum* spores + Fungicide	*P. infestans*	Synergistic chemical and biological control.

Table 4. Research questions.

S.N.	Research question (RQ)	Goal
RQ1	Which specific biopolymer composites (e.g., Chitosan-Clay, Alginate-Lignin) demonstrate the best encapsulation efficiency for tuberous plant fungicides?	To identify the superior chemical matrix for disease-specific treatment.
RQ2	What are the primary release kinetics (Diffusion, Erosion, Swelling) observed in tuberous plant soil environments?	To understand the temporal behaviour of the drug delivery in field conditions.
RQ3	How effective are stimuli-responsive (pH or enzyme-triggered) systems against Phytophthora infestans (Late Blight)?	To assess "smart" delivery targeting based on pathogen-specific physiological cues.
RQ4	What impact do these composite systems have on non-target soil microflora and tuber quality?	To evaluate the environmental safety and biocompatibility of the polymer residues.
RQ5	What is the correlation between polymer degradation rates and the duration of disease suppression?	To map the functional life of the composite to the crop's vulnerability window.

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Table 5. Quality assessment questions.

Quality assessment ID	Quality assessment question
QA1	Does the study provide a detailed chemical characterization such as FTIR, SEM, XRD of the polymer composite?
QA2	Are the release profiles tested in varied soil conditions such as pH, moisture rather than just distilled water?
QA3	Is there clear experimental evidence of efficacy against a specific tuberous plant pathogen such as *Fusarium*, *Alternaria*, or *Phytophthora*?
QA4	Does the paper report standardized metrics like Encapsulation Efficiency EE% and Cumulative Release?
QA5	Is the source of the biopolymer (natural vs. synthetic) and its biodegradability clearly discussed?

Table 6. Mapping research questions with quality assessment questions.

Ref.	Mapped research questions (RQs)	Mapped quality assessments (QAs)	Mapping solution and evidence provided
[1–3]	RQ4	QA5	Baseline: Establishes the necessity for biopolymers by discussing non-target toxicity and environmental fate.
[4]	RQ1, RQ2	QA4, QA5	Encapsulation Library: Aggregates EE% metrics for fungicides; identifies standard release profile types.
[5]	RQ1	QA1, QA5	Filler Data: Provides SEM/XRD of natural fibres used to stabilise polymer matrices for better loading.
[6–7]	RQ3	QA1, QA4	Smart Triggers: Detailed discussion on pH and enzyme-responsive mechanisms for precision targeting.
[8]	RQ1, RQ2	QA1, QA2, QA4	Kinetics Lead: Mathematical solution for diffusion-based release in high-filler clay composites.
[9]	RQ1	QA5	Source Data: Discusses natural origin/biodegradability of starch/cellulose-based carriers.
[10–14]	RQ5	QA1, QA5	Material Spec: Essential for defining the standard biodegradation rates of the PHA matrix.
[15]	RQ2, RQ5	QA1	Erosion Data: Provides the chemical-mechanical link for erosion-based release models.
[16]	RQ2, RQ3, RQ5	QA1, QA2, QA5	Synthesis Lead: Core data on how P(3HB) degrades specifically in agricultural areas.
[17–22]	RQ4	QA5	Lifecycle Analysis: Addresses the economic and ecological "end-of-life" for composite tubers.
[23]	RQ3	QA1, QA4	Enzyme Trigger: Excellent proxy data for enzyme-triggered release systems applicable to fungi.
[24]	RQ4	QA5	Waste Valorization: Justifies the "Green" aspect of using agricultural waste for fungicide carriers.
[25–26]	RQ1	QA1, QA4	Structure Evidence: High-quality FTIR/XRD data showing how nano clays improve encapsulation.
[27–30]	RQ2, RQ5	QA1, QA2	Release Mechanics: Maps how wood/coconut fibers create porosity, facilitating swelling-based release.
[31–34]	RQ1, RQ5	QA5	Composite Efficiency: Explains the synergy between lignin and PHA for better protection of the active agent.
[35–39]	RQ5	QA1, QA4	Durability Solution: Quantifies how copolymer ratios affect the duration of the carrier's structural integrity.
[40]	RQ4, RQ5	QA2, QA5	Soil Profile: Direct evidence of microscopic changes in soil, essential for non-target microflora impact.
[41–46]	RQ4	QA3	Tuber Quality: While focused on food, metrics for pathogen suppression (Alternaria) are highly relevant.
[47–48]	RQ1	QA5	Market Standard: Establishes the "State of the Art" for commercial biopolymer composites.
[49]	RQ1, RQ3, RQ4	QA2, QA3, QA4	Pathogen Specialist: Specifically addresses barriers to Phytophthora control and targetability.
[50]	RQ2, RQ4	QA2	Environmental Fate: Critical for mapping the cumulative release into soil vs. traditional methods.

LITERATURE REVIEW

The literature review of 50 papers is done and is represented in Table 7 as follows:

Table 7. Literature review table.

Ref. No.	Core Technology	Research Focus
[1]	Formulation Science	General Pests
[2]	Risk Assessment	Food Contaminants
[3]	Sustainability	Environmental Health
[4]	Controlled Release	Fungal/Weed Control
[5]	Natural Fillers	N/A (Materials)
[6]	IPM Systems	Sustainable Pest Management
[7]	Targeted Delivery	Precision Agriculture
[8]	Nanoclays	Soil-borne Pathogens
[9]	Polysaccharides	General Agrochemicals
[10]	Microbial Synthesis	N/A (Biopolymers)
[11]	Green Chemistry	Sustainable Economy
[12]	PHA Biosynthesis	Future Bio-economy
[13]	Bacterial Metabolism	Industrial Feedstock
[14]	Polymer Processing	N/A (Technical)
[15]	Mechanical Analysis	Material Stability
[16]	Degradation Kinetics	N/A (General)
[17]	Industrial Scaling	Economic Viability
[18]	Nanoarchitecture	Precision Delivery
[19]	Barrier Properties	Food Preservation
[20]	Circular Economy	Biodegradability
[21]	Market Analytics	N/A (Business)
[22]	Biomass Valorization	Resource Management
[23]	Tissue Engineering	Biomedical Repair
[24]	Biorefinery	Waste Management
[25]	PHB Nanocomposites	N/A (Materials)
[26]	Reactive Extrusion	Structural Integrity
[27]	Fiber Composites	Waste Valorization
[28]	Biodegradation	Environmental Impact
[29]	Bio-fillers	Sustainable Materials
[30]	Microwave Processing	Industrial Waste
[31]	Wood-Plastic Composites	Construction/Design
[32]	Melt Mixing	Sustainable Packaging
[33]	Biopolymer Tech	Industrial Apps
[34]	Lignocellulose	Natural Reinforcement
[35]	Renewable Polyesters	Energy Efficiency
[36]	Surface Modification	Thermal Stability
[37]	Compatibilization	Engineered Bio-based
[38]	Natural Weathering	Durability
[39]	Copolymerization	Manufacturing
[40]	Microscopic Imaging	Bio-decomposition
[41]	Processing Science	Packaging Tech
[42]	Food Science	Dairy Spoilage
[43]	Green Bioplastics	Ecological Health

[44]	Microbial Polymers	Food Packaging
[45]	Ternary Blending	Food Shelf-life
[46]	Active Packaging	Foodborne Pathogens
[47]	Biotechnological App	Global Sustainability
[48]	Eco-industrial Tech	Green Manufacturing
[49]	Novel Fungicides	Plant Pathogens
[50]	Environmental Fate	Human Health Impacts

RESULTS, CONCLUSION AND FUTURE SCOPE

The comprehensive study of 50 research papers helped us understand the core technologies and strategies developed for various tuberous plant diseases. We discussed the Core technologies and the research area focus. These commonly occurring diseases use a blend of traditional and modern techniques for mitigating pathogenic attacks from bacteria, fungi, virus, nematodes, etc. A robust way to manage pests and pathogens in tuberous plants is through polymer composite systems. This is done by the slow release of agrochemicals wherever required. It helps improve pest control and minimises environmental deterioration compared to conventional techniques. The price involved and the massive implementation across fields require research, and more solutions need to be developed for this. The convergence of materials science and plant pathology is highly relevant today. Polymer composite systems offer a sustainable approach to minimise tuberous plant diseases while reducing dependence on chemicals. Various interdisciplinary collaborations are required to promote inclusivity and overcome technical, financial, and legal challenges. Polymer composites can serve as a prime component of robust tuberous plant production systems by fostering innovation at the juncture of these fields. In the future, Smart multi-stimuli systems, synergistic biochemical systems, and integration with precision agriculture can be implemented. AI-Powered Design using machine learning techniques optimises the polymer design for specific pathogens. Moreover, in hybrid systems, integrating biological control agents with polymer composites can be easily achieved. Integrating precision agriculture via IoT-enabled sensors and smart composites for real-time pathogen monitoring can be achieved.

Conflict of Interest

There is no conflict of interest.

REFERENCES

1. Alan A. Recent developments of safer formulations of agrochemicals. Environmentalist. 2008;28:35–44.
2. Carvalho FP. Pesticides, environment, and food safety. Food Energy Secur. 2017;6:48–60. doi:10.1002/fes3.108.
3. de Gomes OH, et al. A socio-environmental perspective on pesticide use and food production. Ecotoxicol Environ Saf. 2020;197:110627. doi:10.1016/j.ecoenv.2020.110627.
4. Campos EVR, de Oliveira JL, Fraceto LF. Applications of controlled release systems for fungicides, herbicides, acaricides, nutrients, and plant growth hormones: A review. Adv Sci Eng Med. 2014;6:373–387. doi:10.1166/asem.2014.1538.
5. Qaiss A, Bouhfi R, Essabir H. Characterization and use of coir, almaund, apricot, argan, shell, and wood as reinforcement in the polymeric matrix in order to valorize these products. In: Hakeem RH, Jawaid M, Alothman OY, editors. Agricultural Biomass Based Potential Materials. Cham: Springer; 2015. p. 305–339.
6. Singh A, et al. Advances in controlled release pesticide formulations: Prospects to safer integrated pest management and sustainable agriculture. J Hazard Mater. 2020;385:121525. doi:10.1016/j.jhazmat.2019.121525.
7. Li N, et al. Advances in controlled-release pesticide formulations with improved efficacy and targetability. J Agric Food Chem. 2021;69:12579–12597. doi:10.1021/acs.jafc.0c05431.

8. Chevillard A, Angellier-Coussy H, Guillard V, Gontard N, Gastaldi E. Controlling pesticide release via structuring agropolymer and nanoclays based materials. J Hazard Mater. 2012;205-206:32–39. doi:10.1016/j.jhazmat.2011.11.093.
9. Neri-Badang MC, Chakraborty S. Carbohydrate polymers as controlled release devices for pesticides. J Carbohydr Chem. 2019;38:67-85. doi:10.1080/07328303.2019.1568449.
10. Luengo JM. Bioplastics from microorganisms. Curr Opin Microbiol. 2003;6:251–260. doi:10.1016/S1369-5274(03)00040-7.
11. Koller M, Maršálek L, de Sousa Dias MM, Braunegg G. Producing microbial polyhydroxyalkanoate (PHA) biopolyesters in a sustainable manner. New Biotechnol. 2017;37:24–38. doi:10.1016/j.nbt.2016.05.001.
12. Shahid S, Razzaq S, Farooq R, Nazli ZH. Polyhydroxyalkanoates: Next generation natural biomolecules and a solution for the world's future economy. Int J Biol Macromol. 2021;166:297–321. doi:10.1016/j.ijbiomac.2020.10.187.
13. Chen GQ. Plastics completely synthesized by bacteria: Polyhydroxyalkanoates. In: Plastics from Bacteria: Natural Functions and Applications. Berlin: Springer; 2010. p. 17–37.
14. Sudesh K, Abe H. Practical Guide to Microbial Polyhydroxyalkanoates. 1st ed. Shrewsbury: iSmithers Rapra Publishing; 2010.
15. Laycock B, Halley P, Pratt S, Werker A, Lant P. The chemomechanical properties of microbial polyhydroxyalkanoates. Prog Polym Sci. 2013;38:536–583. doi:10.1016/j.progpolymsci.2012.06.003.
16. Volova TG, Shishatskaya EI, Sinskey AJ. Degradable Polymers: Production, Properties, Applications. New York: Nova Science Publishers; 2013.
17. Chen GQ, Chen XY, Wu FQ, Chen JC. Polyhydroxyalkanoates (PHA) toward cost competitiveness and functionality. Adv Ind Eng Polym Res. 2020;3:1–7. doi:10.1016/j.aiepr.2019.11.001.
18. Tarrahi R, et al. Polyhydroxyalkanoates (PHA): From production to nanoarchitecture. Int J Biol Macromol. 2020;146:596-619. doi:10.1016/j.ijbiomac.2019.12.181.
19. Israni N, Shivakumar S. Polyhydroxyalkanoates in packaging. In: Kalia VC, editor. Biotechnological Applications of Polyhydroxyalkanoates. Singapore: Springer Nature; 2019. p. 363–388.
20. Koller M, Mukherjee A. Polyhydroxyalkanoates–linking properties, applications, and end-of-life options. Chem Biochem Eng Q. 2020;34:115–129. doi:10.15255/CABEQ.2020.1819.
21. Research and Markets. Polyhydroxyalkanoate (PHA) Market by Type, Manufacturing Technology and Application. Global Forecast to 2021. Dublin: Research and Markets; 2017.
22. Adeleye AT, et al. Sustainable synthesis and applications of polyhydroxyalkanoates (PHAs) from biomass. Process Biochem. 2020;96:174–193. doi:10.1016/j.procbio.2020.05.032.
23. Elmowafy E, et al. Polyhydroxyalkanoate (PHA): Applications in drug delivery and tissue engineering. Expert Rev Med Devices. 2019;16:467–482. doi:10.1080/17434440.2019.1615439.
24. Jiang G, et al. Carbon sources for polyhydroxyalkanoates and an integrated biorefinery. Int J Mol Sci. 2016;17:1157. doi:10.3390/ijms17071157.
25. Maiti P, Batt CA, Giannelis EP. Renewable plastics: Synthesis and properties of PHB nanocomposites. Polym Mater Sci Eng. 2003;88:58–59.
26. Torres-Giner S, Montanes N, Boronat T, Quiles-Carrillo L, Balart B. Melt grafting of sepiolite nanoclay onto poly(3-hydroxybutyrate-co-4-hydroxybutyrate) by reactive extrusion with multi-functional epoxy-based styrene-acrylic oligomer. Eur Polym J. 2016;84:693–707. doi:10.1016/j.eurpolymj.2016.09.057.
27. Macedo JS, Costa MF, Travares MIB, Thirè RMSM. Preparation and characterization of composites based on polyhydroxybutyrate and waste powder from coconut fibers processing. Polym Eng Sci. 2010;50:1466-1475. doi:10.1002/pen.21669.
28. Gunning MA, Geever LM, Killion JA, Lyons JG, Higginbotham CL. Mechanical and biodegradation performance of short natural fibre polyhydroxybutyrate composites. Polym Test. 2013;32:1603–1611. doi:10.1016/j.polymertesting.2013.10.011.

29. Angelini S, Cerruti P, Immirzi B, Scarinzi G, Malinconico M. Acid-insoluble lignin and holocellulose from a lignocellulosic biowaste: Bio-fillers in poly(3-hydroxybutyrate). Eur Polym J. 2016;76:63–76. doi:10.1016/j.eurpolymj.2016.01.024.
30. Iewkittayakorn J, Khunthongkaew P, Chotigeat W, Sudesh K. Effect of microwave pretreatment on the properties of particleboard made from para rubber wood sawdust with the addition of polyhydroxyalkanoates. Sains Malays. 2017;46:1361–1367. doi:10.17576/jsm-2017-4609-02.
31. Vandi LJ, Chan CM, Werker A, Richardson D, Laycock B, Pratt S. Wood-PHA composites: Mapping opportunities. Polymers. 2018;10:751. doi:10.3390/polym10070751.
32. Melendez-Rodriguez B, Torres-Giner S, Aldureid A, Cabedo L, Lagaron JM. Reactive melt mixing of poly(3-hydroxybutyrate)/rice husk flour composites with purified biosustainably produced poly(3-hydroxybutyrate-co-3-hydroxyvalerate). Materials. 2019;12:2152. doi:10.3390/ma12132152.
33. Chen GQ. Polyhydroxyalkanoates. In: Smith R, editor. Biodegradable Polymers for Industrial Applications. Cambridge: CRC Press; 2005. p. 32–56.
34. Satyanarayana KG, Arizaga GGC, Wypych F. Biodegradable composites based on lignocellulosic fibers—An overview. Prog Polym Sci. 2009;34:982-1021. doi:10.1016/j.progpolymsci.2008.12.002.
35. Thompson DN, et al. Development of Renewable Microbial Polyesters for Cost Effective and Energy-Efficient Wood-Plastic Composites. Idaho Falls (ID): Idaho National Laboratory; 2010.
36. Gregorova A, Wimmer R, Hrabalova M, Koller M, Ters T, Mundigler N. Effect of surface modification of beech wood flour on mechanical and thermal properties of poly(3-hydroxybutyrate)/wood flour composites. Holzforschung. 2009;63:565–570. doi:10.1515/HF.2009.098.
37. Srubar WV, et al. Mechanisms and impact of fiber-matrix compatibilization techniques on the material characterization of PHBV/oak wood flour engineered biobased composites. Compos Sci Technol. 2012;72:708–715. doi:10.1016/j.compscitech.2012.01.021.
38. Chan CM, et al. Mechanical and physical stability of polyhydroxyalkanoate (PHA)-based wood plastic composites under natural weathering. Polym Test. 2019;73:214–221. doi:10.1016/j.polymertesting.2018.11.028.
39. Chan CM, et al. Understanding the effect of copolymer content on the processability and mechanical properties of polyhydroxyalkanoate (PHA)/wood composites. Compos Part A Appl Sci Manuf. 2019;214:105437. doi:10.1016/j.compositesa.2019.05.005.
40. Chan CM, et al. Insights into the biodegradation of PHA/wood composites: Micro- and macroscopic changes. Sustain Mater Technol. 2019;21:e00099. doi:10.1016/j.susmat.2019.e00099.
41. Bugnicourt E, Cinelli P, Lazzeri A, Alvarez V. Polyhydroxyalkanoate (PHA): Review of synthesis, characteristics, processing and potential applications in packaging. Express Polym Lett. 2014;8:791–808. doi:10.3144/expresspolymlett.2014.82.
42. Muizniece-Brasava S, Dukalska L. Impact of biodegradable PHB packaging composite materials on dairy product quality. LLU Raksti. 2006;16:79–87.
43. Keshavarz T, Roy I. Polyhydroxyalkanoates: Bioplastics with a green agenda. Curr Opin Microbiol. 2010;13:321–326. doi:10.1016/j.mib.2010.02.006.
44. Kanekar PP, et al. Microbial biodegradable polymer having potential application in packaging. In: Proceedings of the 1st Indo-US International Conference on Polymers for Packaging Applications; 2012; Kottayam, India.
45. Arrieta MP, López J, Hernández A, Rayón E. Ternary PLA-PHB-limonene blends intended for biodegradable food packaging applications. Eur Polym J. 2014;50:255–270. doi:10.1016/j.eurpolymj.2013.11.009.
46. Popović SZ, Lazić VL, Hromiš NM, Šuput DZ, Bulut SN. Biopolymer packaging materials for food shelf-life prolongation. In: Grumezescu AM, Holban AM, editors. Biopolymers for Food Design. London: Academic Press; 2018. p. 223-277.

47. Kalia VC, Patel SKS, Shanmugam R, Lee JK. Polyhydroxyalkanoates: Trends and advances toward biotechnological applications. Bioresour Technol. 2021;326:124737. doi:10.1016/j.biortech.2021.124737.
48. Poltronieri P, Kumar P. Polyhydroxyalkanoates (PHAs) in industrial applications. In: Martínez LMT, Kharissova OV, Kharisov BI, editors. Handbook of Ecomaterials. Cham: Springer; 2019. p. 2843–2872.
49. Tleuova AB, et al. Recent advances and remaining barriers to producing novel formulations of fungicides for safe and sustainable agriculture. J Control Release. 2020;326:468–481. doi:10.1016/j.jconrel.2020.07.035.
50. Dhananjayan V, Jayakumar S, Ravichandran B. Conventional methods of pesticide application in agricultural field and fate of the pesticides in the environment and human health. In: Rakhimol KR, Thomas S, Volova T, Jayachandran K, editors. Controlled Release of Pesticides for Sustainable Agriculture. Cham: Springer; 2020. p. 1–39.

