Journal of
Composites Science

MDPI

Review

Polyhydroxyalkanoates Composites and Blends: Improved Properties and New Applications

Atim J. Emaimo [1,*], Anatoly A. Olkhov [2,3], Alexey L. Iordanskii [3] and Alexandre A. Vetcher [1,4,*]

[1] Institute of Biochemical Technology and Nanotechnology (IBTN), Peoples' Friendship University of Russia (RUDN), 6 Miklukho-Maklaya St, 117198 Moscow, Russia
[2] Scientific Laboratory "Advanced Composite Materials and Technologies", Plekhanov Russian University of Economics, 36 Stremyanny Ln, 117997 Moscow, Russia; aolkhov72@yandex.ru
[3] N.N. Semenov Federal Research Center for Chemical Physics, Russian Academy of Sciences, 4 Kosygin St., 119334 Moscow, Russia; aljordan08@gmail.com
[4] Complementary and Integrative Health Clinic of Dr. Shishonin, 5 Yasnogorskaya St, 117588 Moscow, Russia
* Correspondence: atimabbaomoabba@gmail.com (A.J.E.); avetcher@gmail.com (A.A.V.)

Abstract: Composites of Polyhydroxyalkanoates (PHAs) have been proven to have enhanced properties in comparison to the pure form of these polyesters. Depending on what polymer or material is added to PHAs, the enhancement of different properties is observed. Since PHAs are explored for usage in diverse fields, understanding what blends affect what properties would guide further investigations towards application. This article reviews works that have been carried out with composite variation for application in several fields. Some properties of PHAs are highlighted and composite variation for their modulations are explored.

Keywords: Polyhydroxyalkanoates; composite variation; biodegradation; biocompatibility physical and chemical properties

Citation: Emaimo, A.J.; Olkhov, A.A.; Iordanskii, A.L.; Vetcher, A.A. Polyhydroxyalkanoates Composites and Blends: Improved Properties and New Applications. *J. Compos. Sci.* **2022**, *6*, 206. https://doi.org/10.3390/jcs6070206

Academic Editors: Mohamed Ragoubi, Frédéric Becquart and Ahmed Koubaa

Received: 16 June 2022
Accepted: 13 July 2022
Published: 15 July 2022

1. Introduction

Polyhydroxyalkanoates (PHAs) are biodegradable polymers (specifically polyesters) naturally produced by different types of microorganisms and fermentation. These polymers can be gotten from the combination of different monomers which yield distinct properties. Different monomeric compositions of PHAs have different physical and chemical properties [1]. These diverse properties of PHAs have found different applications in various fields of science and technology. The physical properties, such as the chemical properties, are dependent on the monomer units. Different levels of these properties can be achieved through crystalline modifications and optimizing the processing conditions. One of the numerous important properties of PHAs is their biodegradability. Unlike normal plastics which have raised serious concerns due to their inability to decompose rapidly with mild toxicity, studies have found that PHAs biodegradability puts them up as a viable candidate for a more ecologically friendly plastic [2]. There are different factors that can affect the degradation rate of PHAs. Such factors include environmental conditions, crystallinity, surface area, additives, and so on [3]. Another interesting property of PHAs which have found applications and raised research interests in the field of pharmacology, biomedical engineering, and tissue engineering is their anti-microbial property. Studies have shown that coating biomedical devices with PHAs which have optimized antibacterial properties reduces the probability of biomaterial-associated infections developing [4,5].

The properties of PHAs can be modulated (changed) by combining them with other polymers, materials to form composites. The property of PHA changes, depending on what materials, technical parameters that are used in the formation of these composites. Certain properties such as the rate of degradation, mechanical, antimicrobial, chemical and physical properties can be enhanced or reduced by using composites. Mechanical, thermal, and electrical properties were significantly enhanced with the use of composites made with nanofillers [6]. The effect of composite variation has been observed in other properties of PHAs. This paper is aimed at analyzing the different composite variations that have been tested and their effects on various properties of PHAs.

2. Results

Different studies have been rigorously carried out to observe the effect of composite variation on various properties of PHA. This work shows a review of the relationship between the different composites used and the resulting effect on PHA properties.

2.1. Biocompatibility

2.1.1. Effects of Surface Morphology

The effects of the morphology of the blend between PHBHHx (a member of the PHA family) and PHB (polyhydroxybutyrate) on the biocompatibility of the material was studied. A comparison between [7] pure PHBHHx and PHBHHx/PHB scaffolds with SEM showed that the latter kept its shape well after being dissolved in water, while the PHBHHx scaffold was found to have lost some of its shape after being immersed in water for a long period of time. It was also observed that there was a reduction in the pore size of PHBHHx scaffold after being dissolved compared with that in 2:1 PHBHHx/PHB scaffold. This was observed since salt particles filled all over the space of the materials moving from the surface to the sample's internal space, which resulted in the PHBHHx scaffold having a porous surface. But the s 2:1 PHBHHx/PHB scaffold on the other hand had a continuous surface.

The surface properties (i.e., morphology of a biomaterial have effects on the adhesion of cells to it) [8,9]. In the absence of additions and treatments, PHB films have a coralloid (coral looking) surface which is designed with many protrusions and pores. The attachments of cells to the biomaterial were affected by the irregular nature of the surface morphology. Films with smoother surfaces (i.e., pore free surfaces are more conducive for cell growth than the coral-like ones). Introducing PHBHHx to the blend reduces the size of the pores, thereby giving it a smoother surface, which enhances cell adhesion to the film and growth.

2.1.2. Addition of Bacterial Cellulose or Microcrystalline Cellulose

It was observed that a decrease of melting temperature and influence on the heat of fusion and crystallinity of composites occurred due to the addition of bacterial cellulose (BC) or microcrystalline cellulose (MC) into PHA matrix. Physico-chemical and in vitro methods were used to test biocompatibility. The tested biocomposites met the required pharmacological standards in regards to acidity, absorbance, alkalinity, reducing substances, and other tests. The biocomposites were not found to be cytotoxic compared with how viable the of cell cultures exposed to the untreated cells which served as control group were. Data received from experimental analysis on cell morphology for in vitro cytotoxicity assessment showed cell proliferation of cells that grew in direct contact with the complex compared to control cultures (untreated cultures). The morphological aspects of the treated cells are in good agreement with the results obtained from the MTT viability test, and in conclusion, composites based on poly (3-hydroxybuthyrate) (PHB) and poly (3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) infused with bacterial cellulose (BC) and microcrystalline cellulose (MC) are found to be biocompatible [10].

2.1.3. Biocompatibility for Neural Regeneration

PHAs' useful properties which include biodegradability and non-cytotoxicity, have found use as bio-implantable materials for numerous medical applications [11]. There are some properties of PHAs, however, that have hindered its extensive usage in medical applications, such as the surface hydrophobicity. To improve the hydrophilic properties of PHA, different surface treatments have been considered as effective means. Different strategies, including grafting, ultraviolet treatment, plasma treatment, and surface hydrolysis have been applied to improve the hydrophilicity of the macro-molecular materials.

Yet, these techniques pose some limitations. The grafting technique, for example, makes the surface of the material very unstable due to weak interactions between the masses. Direct UV radiation greatly reduces mechanical resistance properties of polymer films and makes them very brittle. Even plasma treatment can only increase hydrophilicity of temporary surface PHA and the surface tends to revert to its untreated state soon after treatment. Alkali and lipase treatment is proven to be very effective in improving wetting and adhesion properties of polymer surfaces. NaOH acts as a hydrolysis catalyst and lipase is a special enzyme acting on the ester bonds of polymers [12–15].

Other methods have also been recruited to improve the hydrophilic property of PHA, such as electrospinning, blending with other material and bio-modification with different proteins [16–18]. Results of experiments carried out showed that mixing with 10% gelatin reduced the destruction of the spatial structure of PHBHHx and improved the mechanical tensile properties. At the same time, the increased surface porosity and decreased crystallinity caused by gelatin uptake may be beneficial for cell proliferation compared to pure PHBHHx [19].

2.2. Mechanical Properties

2.2.1. Blending PHAs with Plasticizers

Mixing PHAs, specifically PHB with other polymers or with plasticizers, may offer opportunities to move processability forward by bringing down the processing temperature and lessening the brittleness of PHAs based plastics. So, numerous blends containing PHB/PHAs have been examined, and additionally numerous types of plasticizers have been proposed [20,21]. The experimental results report the utilization of plasticizers from materials that are cheap and promptly accessible on the market, and for the most part, with interesting characteristics, such as oxypropylated glycerin (or laprol), glycerol, glycerol triacetate, 4-nonylphenol, 4,40-dihydroxydiphenyl- methane, acetyl tributyl citrate, salicylic ester, acetyl- salicylic corrosive ester, soybean oil, epoxidized soy- bean oil, dibutylphthalate, triethyl citrate, dioctyl phthalate, dioctylsebacate, acetyl tributyl citrate, di-2-ethylhexylphthalate, tri(ethylene glycol) bis(2ethylhexanoate),triacetine, and greasy alcohols with or without glycerol greasy esters, polyethylene glycol (PEG) as well as low molecular weight polyhydroxybutyrate since PHAs with medium chain length are elastomers with low melting point and a relatively lower degree of crystallinity [22,23].

2.2.2. Adding Hydrophobically Treated CNCs to Form a PHA Composite

By adding a hydrophobically treated CNC to PHA composites, an improved breaking point elongation by up to 301% was observed, with almost no reduction in its elastic modulus compared to that of the pure PHA sample. Apparently double salinized CNC also played a similar role as the nucleating agent for PHA composites. This CNC PHA composites with ductility on the high side can improve the mechanical properties of PHA composites and make them more suitable for mass production [24].

2.2.3. Incorporation of Natural Rubber into PHBV

Incorporation of incredibly viscous high-molecular weight natural rubber (HMW-NR, gel extracted from NR) into PHBV can enhance its properties. HMW-NR isn't always commercially available, negatively affecting commercialization of the PHBV/rubber blends. The PHBV/NR blends had been fabricated via a -step extrusion technique with the use of a twin-screw extruder. The blends contained levels with crosslinked rubber being dispersed in PHBV, and had clean rubber loading based variations in performance. The thermal balance and melting power of the blends had been superior over pristine PHBV, indicating advanced processability [25].

2.2.4. Using Nanofillers to Enhance Barrier Properties

One of the most important characteristics of materials currently used for food packaging are elasticity and permeability [26]. Biodegradable nanofiller composites have important features which can be found in metal-based packaging, and in addition they also have other excellent properties such as mechanical properties, thermodynamic properties and ecologically friendly properties, and so on. Nanofiller composites can be significantly improve high barrier properties of polymers [27]. Due to the presence of nanofillers, there is a molecular pathway that increases as it passes through the substrate. Increase in the diffusion path of gas or other water vapor molecules through the polymer, significantly slows the penetration rate of the polymer and effectively enhances the polymer's barrier characteristics.

The surface topography of a pure PHA sample, and composite samples with graphene nanoplatelets (GNPs) were observed under a SEM. The neat PHA polymer had a regular cross-section with no air bubbles or holes visible through it. The nanofillers were uniformly dispersed throughout the polymer matrix. The roughest surface was found in the GNPs-based nanocomposites, with roughness increasing with GNPs loading and a higher number of restacked flakes and agglomerates. While the distribution of both fillers appeared more homogeneous. The polymer-filler interface appeared to be intact for the majority of the flakes in both samples, with no gaps or voids. This fact is presumed to achieve maximum reinforcement efficiency. A small number of flakes could also be seen to have rolled up as a result of the melt-mixing procedure within the internal mixer. When GNPs were mixed with low-modulus elastomers at high shear rates, this occurrence is common. It is worth noting that the compression molding procedure used after mixing resulted in a preferred orientation for both the GNPs and the carbon nanofibers (CNFs) in the axial direction of the samples. Even if the degree of orientation was not very high in this case, it was predicted that it will contribute to improve in-plane mechanical properties and modulation of conduction mechanisms [28–30].

2.3. Biodegradation

2.3.1. Effects of Water Absorption and Diffusion on Degradability

Water absorption and diffusion determine the rate of hydrolytic degradation in fibrous biopolyesters. The chemical nature (hydrophobicity–hydrophilicity ratio) of the macromolecules, polymer crystallinity, surface special features, and volume morphology, as well as fibril porosity, interfibrillar space of the mats, and other structural factors, all influence water absorption capacity. The isotherms of water absorption of PHB-PLA blends were obtained and the deviation from linearity (the Henry low) was analyzed by the simplified model. A dependency of these parameters on the ratio of PHB to PLA in the blend was observed [31,32].

2.3.2. PHA Blends and Biodegradation

Over a 24-week period, the biodegradation behavior of polyhydroxyalkanoate (PHA) composites containing 10% distiller's dried grains with solubles (DDGS) was characterized and evaluated by comparing to pure PHA. Weight loss was approximately 6 times greater for the PHA/DDGS 90/10 composites after 24 weeks than for unaltered PHA under identical conditions [33]. Composite samples with varying wood contents (0, 20, and 50% wt) were buried in soil at a field trial site in Australia's subtropical region, together with polylactic acid (PLA) and polyethylene (PE) based wood composites as controls. Under identical conditions, the degradation rate of the PHBV/WF composites increased with wood content, with weight loss after 12 months being 5 times greater for PHBV/50 wt percent WF than for neat PHBV plaques [34].

2.4. Electrical and Thermal Properties

2.4.1. Thermal Properties

The thermal stability of composites can be improved by certain treatments relating to the removal of pectin, cellulose, and other substances of the filler. When fiber-matrix interaction improves, the thermal degradation reduces. Likewise, reactive agents impact the thermal behavior of composites. For example, the additive DCP (>0.1 phr), in a blend of PHBV–miscanthus (70–30 wt%), reduces the melting temperature (Tm) of the blend by reducing crystallinity. In some cases, additives mask the nucleating effect of the vegetable fiber in the polymeric matrix. In addition, the plasticizers commonly used for internal lubrication increase mobility and lower the glass transition temperature (Tg). Plasticizer loss usually appears at the beginning of the thermogravimetric analysis (TGA) curve. This behavior is common with PHB composites. Uses glycerol and triethyl citrate (TEC) [35–39].

Both GNPs and CNFs significantly improve the thermal stability of nanocomposites, with no discernible difference between them. In general, higher GNP loadings provide better thermal stability than hybrids, implying that higher loadings of high aspect ratio materials provide a bigger barrier to degradation product diffusion [40].

2.4.2. Electrical Properties

Nanocellulose bio-composites are extensively utilized in medical, electronics, packaging, and other fields. They are presently used for the improvement of flexible digital gadgets. Studies have experimentally proven the benefits of nanoscale, thereby reinforcing the usage of cellulose nanofibers. Composites were gotten by improving diverse forms of resin, using BC nanofibers. As BC nanofibers are bundles of semi-crystalline and prolonged cellulose chains, the obtained nanocomposites aren't the best in terms of flexibility, however additionally produce excessive mechanical energy unlike low carbon steel and unusual coefficients of thermal enlargement unlike silicon, which makes the composite appropriate for applications. Moreover, success has been achieved in depositing an electroluminescent layer (comprised of natural light-emitting diodes) on those BC nanocomposites. Correctly organized poly(lactic acid) cellulose-primarily based on bio degradable nanocomposites can enhance the mechanical ports and thermal stability of the materials [41–44].

2.5. Antimicrobial Properties

2.5.1. PHA–Vegetal Fiber Composites

Natural fibers are primarily composed of cellulose, hemicellulose and lignin, with different physical and chemical properties. Although various natural fibers have been used to enhance PHA, there are some problems with including them. For example, cellulose provides fiber strength, but is less compatible with hydrophobic polymers such as PHA. Hemicellulose is both amorphous and hydrophilic due to the hydroxyl and acetyl groups. Therefore, its mechanical properties are low and retain moisture. The lining is aromatic and amorphous, but less hydrophilic than the other ingredients. These properties result in poor interfacial adhesion between the fiber and the matrix, forming polar groups and poor dispersion within the matrix. Therefore, various pretreatments have been used to reduce fiber polarity and water absorption, improve the affinity between the filler and the matrix, and improve efficient stress transfer from the matrix to the fiber [45–51].

2.5.2. PHAs as Controlled Drug Release Systems

PHAs have been used as a matrix to create slow-release antibiotic delivery formulations, which provide antimicrobial, antifungal, anti-biofilm, anti-inflammatory, and virucidal properties depending on the conjugated/enclosed therapeutic agent. Furthermore, the antimicrobial activity that PHAs or their derivatives have been reported to have should not be overlooked. Films based on PHB with antimicrobial activity were created by incorporating eugenol at concentrations ranging from 10 to 200 mg/g of PHB, and their antimicrobial activity was tested against a variety of spoilage bacteria, foodborne pathogens, and fungi, including *S. aureus*, *E. coli*, *S. typhimurium*, *Bacillus cereus*, *Aspergillus flavus*, *Aspergillus niger*, etc.

Tetracycline was encapsulated into polymeric microspheres via double emulsion-solvent evaporation method. The antibacterial activity was tested against two commonly periodontitis-causing bacteria *Porphyromonas gingivalis* and *Actinobacillus actinomycetemcomitans*. The results suggested the potential use of PHB microspheres loaded with tetracycline for slow-release delivery system [52,53].

2.5.3. PHAs in Wound Healing

PHB-gelatin nanomesh pre-coated with ostholamide (a natural coumarin synthesized from osthole) and collagen achieve mechanical stability in wound repair. The coated nanomesh demonstrated sustained ostholamide release and, as a result, antibacterial activity against the bacteria, indicating a possible future use in wound healing [54,55].

The findings of some studies suggested that drug-loaded degradable polymeric microparticles might be finding applications for skin defect treatment. The effectiveness of using P(3HB/4HB) nonwoven membranes on model skin defects in Wistar rats was investigated in this study. Wounds healed 1.4 times faster under the P(3HB/4HB) membrane carrying cells than under the cell-free membrane and 3.5 times faster than under the eschar (control). On Day 14, the "membrane + cells" group experienced complete healing [56].

3. Discussion

The inherent properties of PHAs that limits their usage in diverse field can be overcome through several modification processes (Figure 1) including the use of blends (i.e., the combination of these polyesters with other materials in composites) [57]. PHA chemical modification approaches are summarized on Figure 2 [58] and general scheme for its production which was discussed in [59] is graphically exhibited on Figure 3.

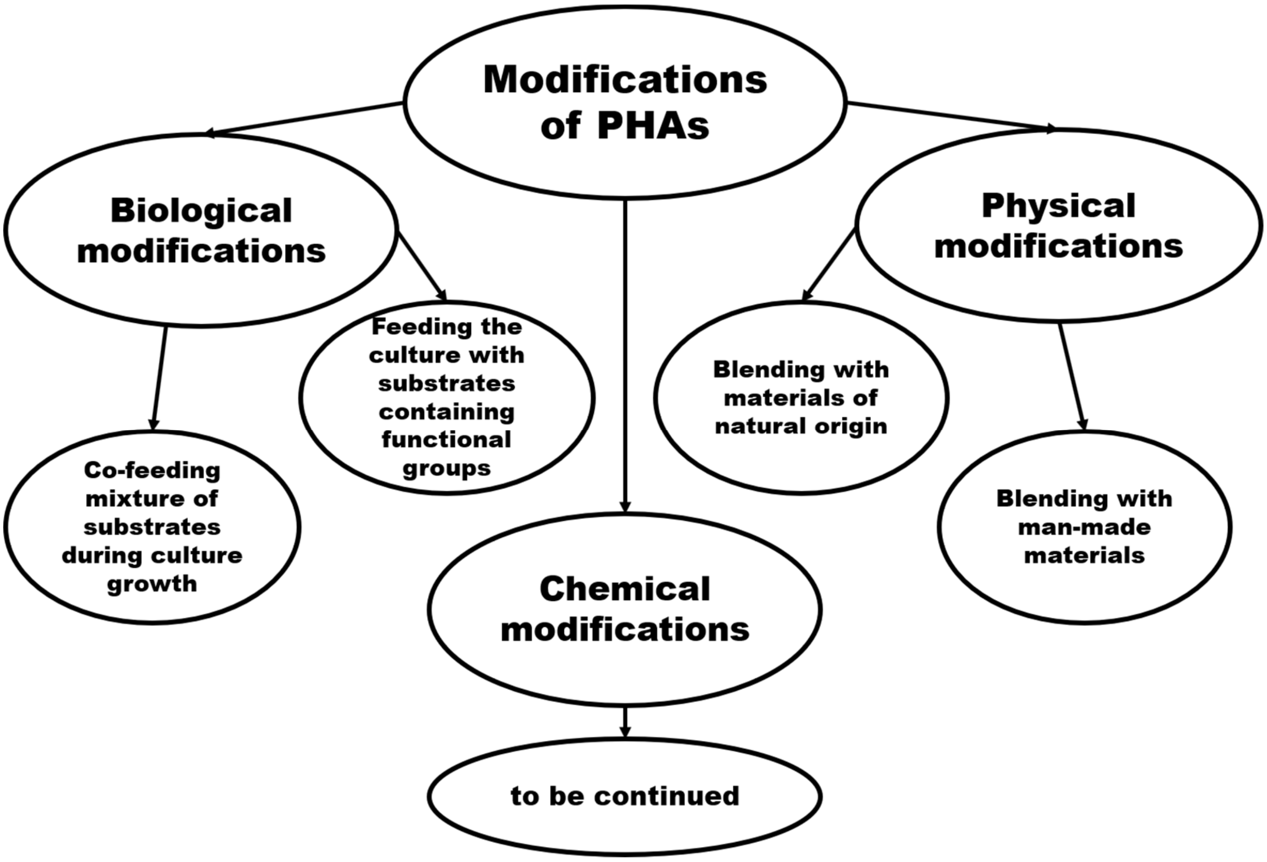


Figure 1. PHA modification methods.

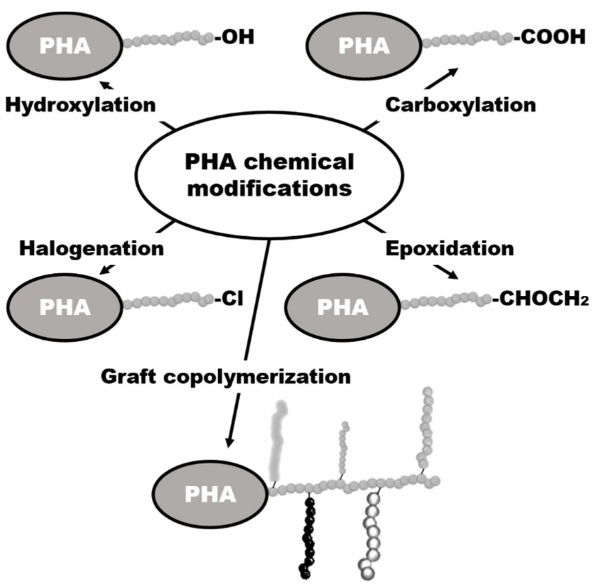


Figure 2. PHA chemical modifications.

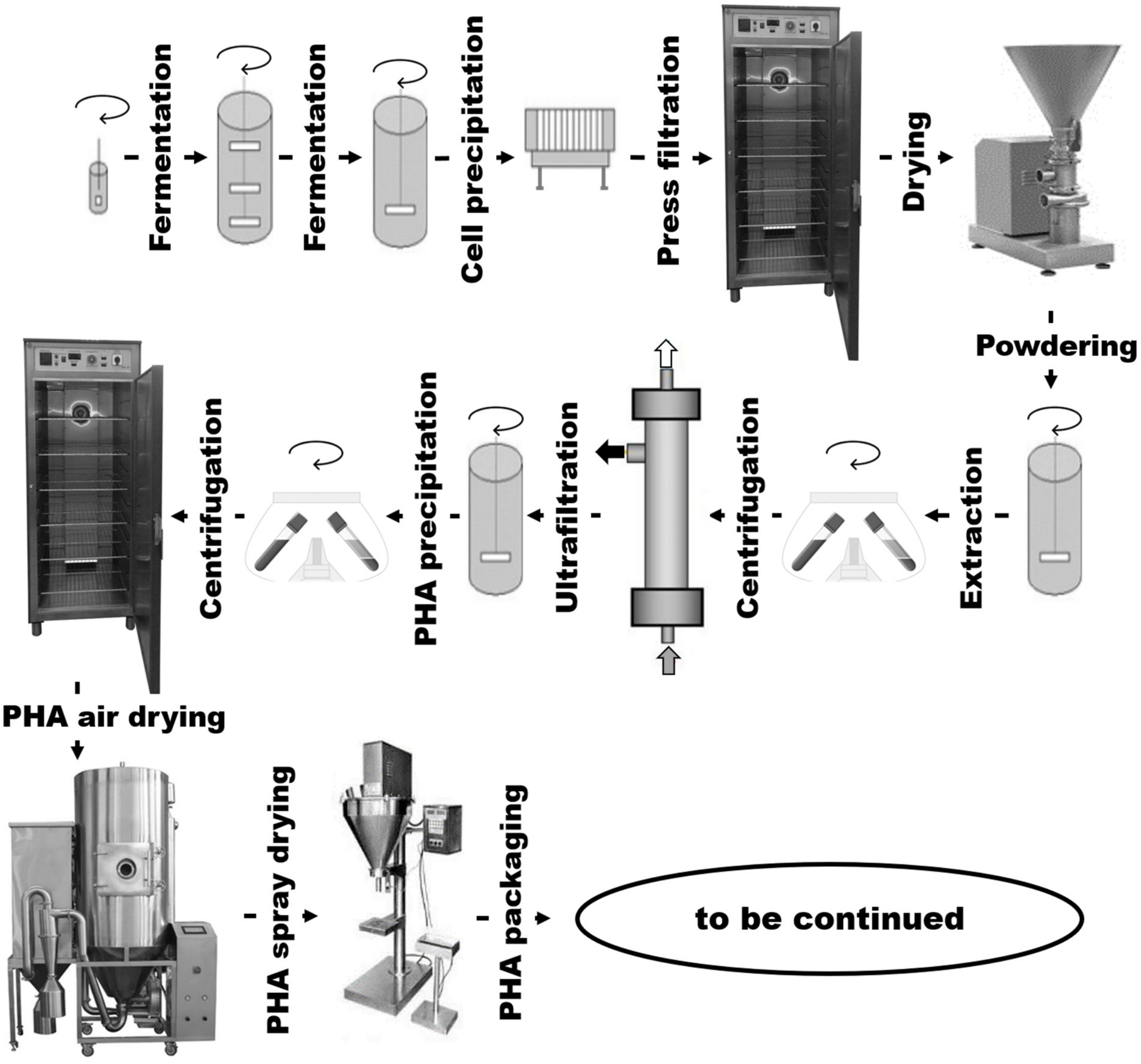


Figure 3. A general scheme for PHA production.

Studies have proven that combining different types of PHAs (see Figure 4) in right proportions with other material significantly enhances wide variety of their properties [60]. These reports have further broadened current and perspective applications of PHA-based materials (Table 1).

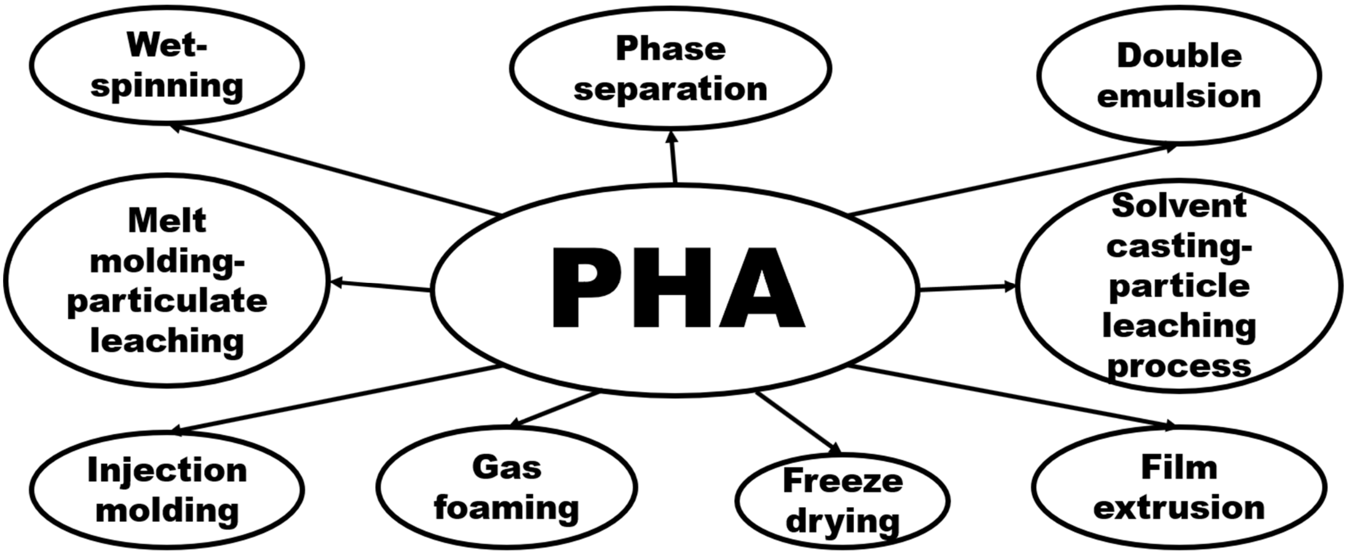
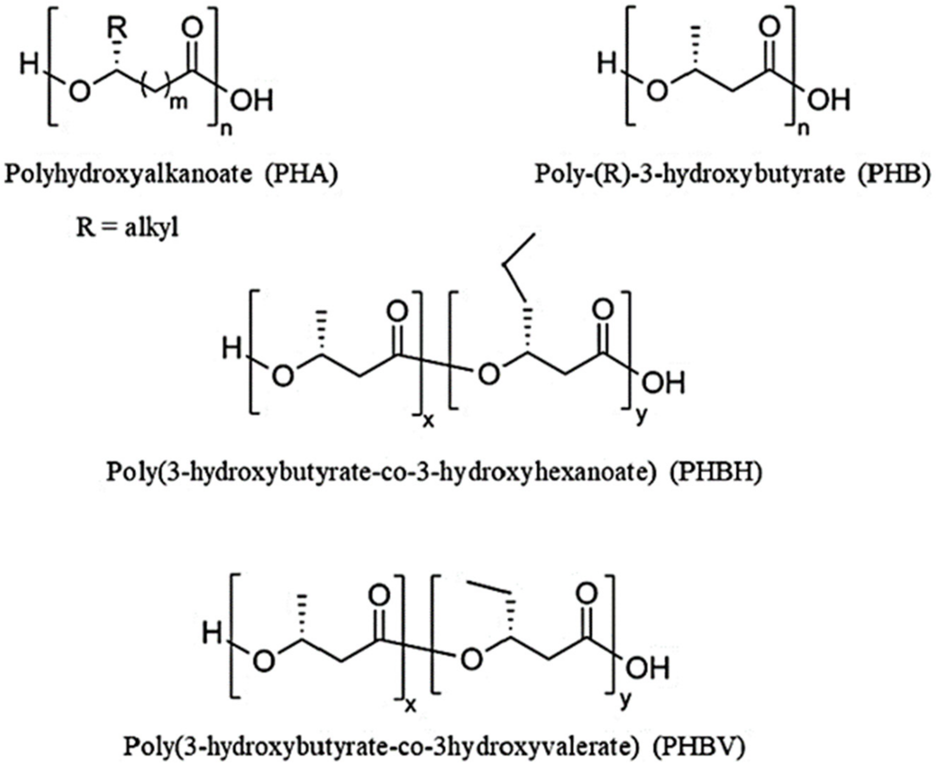


Figure 4. A scheme for PHA production specifically for biomedical applications.

On Figure 5 the molecular structures of commercially available at the industrial scale PHAs [61] is demonstrated.



Polyhydroxyalkanoate (PHA)

R = alkyl

Poly-(R)-3-hydroxybutyrate (PHB)

Poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) (PHBH)

Poly(3-hydroxybutyrate-co-3hydroxyvalerate) (PHBV)

Figure 5. Molecular structure of PHAs available at an industrial scale.

SEM studies demonstrated significant variability on the nanolevel 3D structures of the ES mixtures P(3HB): mcl-PHA [62] and foams PLLA/PHA [63].

Table 1. This table shows a comprehensive summary of this article in a tabular form.

Property	Composite	Effect	Reference
Biodegradation	PHBHHx/normal plastics	Blends degrade considerably faster than typical plastics	[64]
	OMW/PHB film	Accelerated rate of degradation noted	[65]
	UPE/PHB	Significant weight loss noted after 30 days	[66]
Biocompatibility	PHBHHx/PHB	Reduction in pore size and enhanced cell adhesion to film	[8]
	PHBHHx/gelatin	Increase in surface porosity and decrease in crystallinity	[19]
Physical	PHBV–miscanthus	Increased tensile strength	[35]
	+resin	Increased thermal ability	[44]
	CNC/PHA	High ductility	[24]
	PHBV/NR	Better melting power and enhanced processability	[25]
Antimicrobial	P(3HB/4HB)	Wounds healed 3.5 time faster than control	[56]
	PHB + tetracycline	Suggested for controlled drug delivery	[52,53,67]

Experiments have been carried out to observe the bio-nanocomposites based on PHAs and have proven to have positive effects on properties such as the size of the surface area of its active sites. Another example is the tensile strength of a nanocomposite which was drastically enhanced by as high as 300% when observed in a blend of 80PHB/20PCL/1stearate Mg-Al LDH.

4. Conclusions

Other studies demonstrated that these properties are not only dependent on the nature of the composites and ratio of the components but can also be dependent on the material production process. Therefore, to fully optimize certain properties more studies comparing the results of these different combinations of factors should be carried out. Such knowledge would enable the easy application of these composites in solving various problems in various fields of life [58,68–76].

Author Contributions: Conceptualization, A.A.O. and A.A.V.; methodology, A.L.I. and A.A.V.; software, A.A.V.; validation, A.J.E.; formal analysis, A.J.E.; investigation, A.J.E.; resources, A.J.E.; data curation, A.J.E.; writing—original draft preparation, A.J.E. and A.A.V.; writing—review and editing, A.J.E. and A.A.V.; visualization, A.J.E. and A.A.V.; supervision, A.A.O., A.L.I., and A.A.V.; project administration, A.A.V.; funding acquisition, A.A.V. All authors have read and agreed to the published version of the manuscript.

Funding: This paper has been supported by the RUDN University Strategic Academic Leadership Program.

Acknowledgments: Alexandre A. Vetcher is grateful to the RUDN University Strategic Academic Leadership Program for the support.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Samrot, A.V.; Samanvitha, S.K.; Shobana, N.; Renitta, E.R.; Senthilkumar, P.; Kumar, S.S.; Abirami, S.; Dhiva, S.; Bavanilatha, M.; Prakash, P.; et al. Polymers the Synthesis, Characterization and Applications of Polyhydroxyalkanoates (PHAs) and PHA-Based Nanoparticles. *Polymers* **2021**, *13*, 3302. [CrossRef] [PubMed]
2. Zhila, N.O.; Sapozhnikova, K.Y.; Kiselev, E.G.; Vasiliev, A.D.; Nemtsev, I.V.; Shishatskaya, E.I.; Volova, T.G. Properties of Degradable Polyhydroxyalkanoates (PHAs) Synthesized by a New Strain, Cupriavidus Necator IBP/SFU-1, from Various Carbon Sources. *Polymers* **2021**, *13*, 3142. [CrossRef] [PubMed]
3. Ong, S.Y.; Chee, J.Y.; Sudesh, K. Degradation of Polyhydroxyalkanoate (PHA): A Review. *J. Sib. Fed. University. Biol.* **2017**, *10*, 21–225. [CrossRef]
4. Alejandra, R.-C.; Guillem-Marti, J.; Lopez, O.; Manero, J.M.; Rupérez, E. Antimicrobial PHAs Coatings for Solid and Porous Tantalum Implants. *Colloids Surf. B Biointerfaces* **2019**, *182*, 110317. [CrossRef]
5. Rodriguez-Contreras, A. Recent Advances in the Use of Polyhydroyalkanoates in Biomedicine. *Bioengineering* **2019**, *6*, 82. [CrossRef] [PubMed]

6. Sun, J.; Shen, J.; Chen, S.; Cooper, M.A.; Fu, H.; Wu, D.; Yang, Z. Polymers Nanofiller Reinforced Biodegradable PLA/PHA Composites: Current Status and Future Trends. *Polymers* **2018**, *10*, 505. [CrossRef]
7. Kai, Z.; Ying, D.; Guo-Qiang, C. Effects of Surface Morphology on the Biocompatibility of Polyhydroxyalkanoates. *Biochem. Eng. J.* **2003**, *16*, 115–123. [CrossRef]
8. Ruan, D.; Wu, C.; Deng, S.; Zhang, Y.; Guan, G. The Anatase Phase of Nanotopography Titania with Higher Roughness Has Better Biocompatibility in Osteoblast Cell Morphology and Proliferation. *BioMed Res. Int.* **2020**, *2020*, 8032718. [CrossRef]
9. Suárez-Franco, J.L.; García-Hipólito, M.; Surárez-Rosales, M.Á.; Fernández-Pedrero, J.A.; Álvarez-Fregoso, O.; Juárez-Islas, J.A.; Álvarez-Pérez, M.A. Effects of Surface Morphology of ZnAl2O4 Ceramic Materials on Osteoblastic Cells Responses. *J. Nanomater.* **2013**, *2013*. [CrossRef]
10. Râpă, M.; Zaharia, C.; Stanescu, P. Grosu E. Biocompatibility of PHAs Biocomposites Obtained by Melt Processing. *Mater. Plast.* **2015**, *52*, 295–300.
11. Chen, G.-Q.; Wu, Q. The Application of Polyhydroxyalkanoates as Tissue Engineering Materials. *Biomaterials* **2005**, *26*, 6565–6578. [CrossRef] [PubMed]
12. Ren, Y.; Wang, C.; Qiu, Y. Aging of Surface Properties of Ultra High Modulus Polyethylene Fibers Treated with He/O2 Atmospheric Pressure Plasma Jet. *Surf. Coat. Technol.* **2008**, *202*, 2670–2676. [CrossRef]
13. Ma, Z.; Gao, C.; Gong, Y.; Shen, J. Chondrocyte Behaviors on Poly-l-Lactic Acid (PLLA) Membranes Containing Hydroxyl, Amide or Carboxyl Groups. *Biomaterials* **2003**, *24*, 3725–3730. [CrossRef]
14. Shangguan, Y.-Y.; Wang, Y.-W.; Wu, Q.; Chen, G.-Q. The Mechanical Properties and in Vitro Biodegradation and Biocompatibility of UV-Treated Poly(3-Hydroxybutyrate-Co-3-Hydroxyhexanoate). *Biomaterials* **2006**, *27*, 2349–2357. [CrossRef]
15. Benavente, J.; Vázquez, M.I. Effect of Age and Chemical Treatments on Characteristic Parameters for Active and Porous Sublayers of Polymeric Composite Membranes. *J. Colloid Interface Sci.* **2004**, *273*, 547–555. [CrossRef]
16. Lee, I.S.; Kwon, O.H.; Meng, W.; Kang, I.-K.; Ito, Y. Nanofabrication of Microbial Polyester by Electrospinning Promotes Cell Attachment. *Macromol. Res.* **2004**, *12*, 374–378. [CrossRef]
17. Dong, C.-L.; Li, S.-Y.; Wang, Y.; Dong, Y.; Tang, J.Z.; Chen, J.-C.; Chen, G.-Q. The Cytocompatability of Polyhydroxyalkanoates Coated with a Fusion Protein of PHA Repressor Protein (PhaR) and Lys-Gln-Ala-Gly-Asp-Val (KQAGDV) Polypeptide. *Biomaterials* **2012**, *33*, 2593–2599. [CrossRef]
18. You, M.; Peng, G.; Li, J.; Ma, P.; Wang, Z.; Shu, W.; Peng, S.; Chen, G.-Q. Chondrogenic Differentiation of Human Bone Marrow Mesenchymal Stem Cells on Polyhydroxyalkanoate (PHA) Scaffolds Coated with PHA Granule Binding Protein PhaP Fused with RGD Peptide. *Biomaterials* **2011**, *32*, 2305–2313. [CrossRef]
19. Wang, Y.-W.; Wu, Q.; Chen, G.-Q. Gelatin Blending Improves the Performance of Poly(3-Hydroxybutyrate-Co-3-Hydroxyhexanoate) Films for Biomedical Application. *Biomacromolecules* **2005**, *6*, 566–571. [CrossRef]
20. Bijarimi, M.; Ahmad, S.; Rasid, R. Mechanical, Thermal and Morphological Properties of Poly(Lactic Acid)/Epoxidized Natural Rubber Blends. *J. Elastomers Plast.* **2014**, *46*, 338–354. [CrossRef]
21. Shen, L.; Haufe, J.; Patel, M.K. *Product Overviw and Market Projection of Emerging Bio-Based Plastics. PRO-BIP 2009*; Utrecht University: Utrecht, The Netherlands, 2009; 243 p, Available online: https://plasticker.de/docs/news/PROBIP2009_Final_June_2009.pdf (accessed on 26 June 2022).
22. Hong, S.-G.; Heng Wei, H.; Ye, M.-T. Thermal Properties and Applications of Low Molecular Weight Polyhydroxybutyrate. *J. Therm. Anal. Calorim.* **2012**, *111*, 1243–1250. [CrossRef]
23. 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. [CrossRef]
24. Jo, J.; Kim, H.; Jeong, S.Y.; Park, C.; Hwang, H.S.; Koo, B. Changes in Mechanical Properties of Polyhydroxyalkanoate with Double Silanized Cellulose Nanocrystals Using Different Organosiloxanes. *Nanomaterials* **2021**, *11*, 1542. [CrossRef] [PubMed]
25. Zhao, X.; Venoor, V.; Koelling, K.; Cornish, K.; Vodovotz, Y. Bio-Based Blends from Poly(3-Hydroxybutyrate-Co-3-Hydroxyvalerate) and Natural Rubber for Packaging Applications. *J. Appl. Polym. Sci.* **2018**, *136*, 47334. [CrossRef]
26. Johannson, C. Bio-Nanocomposites for Food Packaging Applications. In *Nanocomposites with Biodegradable Polymers*; Oxford University Press: Oxford, UK, 2011; pp. 348–367.
27. Sinha Ray, S.; Okamoto, M. Polymer/Layered Silicate Nanocomposites: A Review from Preparation to Processing. *Prog. Polym. Sci.* **2003**, *28*, 1539–1641. [CrossRef]
28. Cataldi, P.; Condurache, O.; Spirito, D.; Krahne, R.; Bayer, I.S.; Athanassiou, A.; Perotto, G. Keratin-Graphene Nanocomposite: Transformation of Waste Wool in Electronic Devices. *ACS Sustain. Chem. Eng.* **2019**, *7*, 12544–12551. [CrossRef]
29. Liu, M.; Kinloch, I.A.; Young, R.J.; Papageorgiou, D.G. Modelling Mechanical Percolation in Graphene-Reinforced Elastomer Nanocomposites. *Compos. Part B Eng.* **2019**, *178*, 107506. [CrossRef]
30. Cataldi, P.; Steiner, P.; Raine, T.; Lin, K.; Kocabas, C.; Young, R.J.; Bissett, M.; Kinloch, I.A.; Papageorgiou, D.G. Multifunctional Biocomposites Based on Polyhydroxyalkanoate and Graphene/Carbon Nanofiber Hybrids for Electrical and Thermal Applications. *ACS Appl. Polym. Mater.* **2020**, *2*, 3525–3534. [CrossRef]
31. Iordanskii, A.L.; Karpova, S.G.; Olkhov, A.; Borovikov, P.I.; Kildeeva, N.R.; Liu, Y. Structure-Morphology Impact upon Segmental Dynamics and Diffusion in the Biodegradable Ultrafine Fibers of Polyhydroxybutyrate-Polylactide Blends. *Eur. Polym. J.* **2019**, *117*, 208–216. [CrossRef]

32. Olkhov, A.A.; Tyubaeva, P.M.; Vetcher, A.A.; Karpova, S.G.; Kurnosov, A.S.; Rogovina, S.Z.; Iordanskii, A.L.; Berlin, A.A. Aggressive Impacts Affecting the Biodegradable Ultrathin Fibers Based on Poly(3-Hydroxybutyrate), Polylactide and Their Blends: Water Sorption, Hydrolysis and Ozonolysis. *Polymers* **2021**, *13*, 941. [CrossRef]
33. Madbouly, S.A.; Schrader, J.A.; Srinivasan, G.; Liu, K.; McCabe, K.G.; Grewell, D.; Graves, W.R.; Kessler, M.R. Biodegradation Behavior of Bacterial-Based Polyhydroxyalkanoate (PHA) and DDGS Composites. *Green Chem.* **2014**, *16*, 1911–1920. [CrossRef]
34. Chan, C.; Vandi, L.-J.; Pratt, S.; Halley, P.; Richardson, D.; Werker, A.; Laycock, B. Insights into the Biodegradation of PHA/Wood Composites: Micro- and Macroscopic Changes. *Sustain. Mater. Technol.* **2019**, *21*, e00099. [CrossRef]
35. Muthuraj, R.; Misra, M.; Mohanty, A.K. Reactive Compatibilization and Performance Evaluation of Miscanthus Biofiber Reinforced Poly(Hydroxybutyrate-Co-Hydroxyvalerate) Biocomposites. *J. Appl. Polym. Sci.* **2017**, *134*. [CrossRef]
36. El-Hadi, A.M. Increase the Elongation at Break of Poly (Lactic Acid) Composites for Use in Food Packaging Films. *Nat. Publ. Group* **2017**, *7*, 46767. [CrossRef]
37. Chan, C.M.; Vandi, L.-J.; Pratt, S.; Halley, P.; Richardson, D.; Werker, A.; Laycock, B. Composites of Wood and Biodegradable Thermoplastics: A Review. *Polym. Rev.* **2018**, *58*, 444–494. [CrossRef]
38. Guo, Y.; Wang, L.; Chen, Y.; Luo, P.; Chen, T. Properties of Luffa Fiber Reinforced PHBV Biodegradable Composites. *Polymers* **2019**, *11*, 1765. [CrossRef]
39. Vizireanu, S.; Mihaela Panaitescu, D.; Nicolae, C.A.; Nicoleta Frone, A.; Chiulan, I.; Daniela Ionita, M.; Satulu, V.; Carpen, L.G.; Petrescu, S.; Birjega, R.; et al. Cellulose Defibrillation and Functionalization by Plasma in Liquid Treatment. *Sci. Rep.* **2018**, *8*, 15473. [CrossRef]
40. Bao, C.; Song, L.; Xing, W.; Yuan, B.; Wilkie, C.; Huang, J.; Guo, Y.; Hu, Y. Preparation of Graphene by Pressurized Oxidation and Multiplex Reduction and Its Polymer Nanocomposites by Masterbatch-Based Melt Blending. *J. Mater. Chem.* **2012**, *22*, 6088–6096. [CrossRef]
41. Petersson, L.; Kvien, I.; Oksman, K. Structure and Thermal Properties of Poly(Lactic Acid)/Cellulose Whiskers Nanocomposite Materials. *Compos. Sci. Technol.* **2007**, *67*, 2535–2544. [CrossRef]
42. Yano, H.; Sugiyama, J.; Nakagaito, A.N.; Nogi, M.; Matsuura, T.; Hikita, M.; Handa, K. Optically Transparent Composites Reinforced with Networks of Bacterial Nanofibers. *Adv. Mater.* **2005**, *17*, 153–155. [CrossRef]
43. Eichhorn, S.J.; Dufresne, A.; Aranguren, M.; Marcovich, N.E.; Capadona, J.R.; Rowan, S.J.; Weder, C.; Thielemans, W.; Roman, M.; Renneckar, S.; et al. Review: Current International Research into Cellulose Nanofibres and Nanocomposites. *J. Mater. Sci.* **2010**, *45*, 1–33. [CrossRef]
44. Nogi, M.; Yano, H. Transparent Nanocomposites Based on Cellulose Produced by Bacteria Offer Potential Innovation in the Electronics Device Industry. *Adv. Mater.* **2008**, *20*, 1849–1852. [CrossRef]
45. Cazón, P.; Velázquez, G.; Vázquez, M. Regenerated Cellulose Films Combined with Glycerol and Polyvinyl Alcohol: Effect of Moisture Content on the Physical Properties. *Food Hydrocoll.* **2020**, *103*, 105657. [CrossRef]
46. Bousfield, G.; Morin, S.; Jacquet, N.; Richel, A. Extraction and Refinement of Agricultural Plant Fibers for Composites Manufacturing. *Comptes Rendus Chim.* **2018**, *21*, 897–906. [CrossRef]
47. Melo, J.D.D.; Carvalho, L.F.M.; Medeiros, A.M.; Souto, C.R.O.; Paskocimas, C.A. A Biodegradable Composite Material Based on Polyhydroxybutyrate (PHB) and Carnauba Fibers. *Compos. Part B Eng.* **2012**, *43*, 2827–2835. [CrossRef]
48. Chilali, A.; Assarar, M.; Zouari, W.; Kebir, H.; Ayad, R. Mechanical Characterization and Damage Events of Flax Fabric-Reinforced Biopolymer Composites. *Polym. Polym. Compos.* **2020**, *28*, 631–644. [CrossRef]
49. Pasangulapati, V.; Ramachandriya, K.D.; Kumar, A.; Wilkins, M.R.; Jones, C.L.; Huhnke, R.L. Effects of Cellulose, Hemicellulose and Lignin on Thermochemical Conversion Characteristics of the Selected Biomass. *Bioresour. Technol.* **2012**, *114*, 663–669. [CrossRef]
50. Pérez, J.; Muñoz-Dorado, J.; de la Rubia, T.; Martínez, J. Biodegradation and Biological Treatments of Cellulose, Hemicellulose and Lignin: An Overview. *Int. Microbiol.* **2002**, *5*, 53–63. [CrossRef]
51. Meng, D.-C.; Shen, R.; Yao, H.; Chen, J.-C.; Wu, Q.; Chen, G.-Q. Engineering the Diversity of Polyesters. *Curr. Opin. Biotechnol.* **2014**, *29*, 24–33. [CrossRef]
52. Seymour, R.A.; Heasman, P.A. Tetracyclines in the Management of Periodontal Diseases. *J. Clin. Periodontol.* **2005**, *22*, 22–35. [CrossRef]
53. Panith, N.; Assavanig, A.; Lertsiri, S.; Bergkvist, M.; Surarit, R.; Niamsiri, N. Development of Tunable Biodegradable Polyhydroxyalkanoates Microspheres for Controlled Delivery of Tetracycline for Treating Periodontal Disease. *J. Appl. Polym. Sci.* **2016**, *133*, 44128–44140. [CrossRef]
54. Ke, Y.; Liu, C.; Zhang, X.; Xiao, M.; Wu, G. Surface Modification of Polyhydroxyalkanoates toward Enhancing Cell Compatibility and Antibacterial Activity. *Macromol. Mater. Eng.* **2017**, *302*, 1700258. [CrossRef]
55. Kandhasamy, S.; Perumal, S.; Madhan, B.; Umamaheswari, N.; Banday, J.A.; Perumal, P.T.; Santhanakrishnan, V.P. Synthesis and Fabrication of Collagen-Coated Ostholamide Electrospun Nanofiber Scaffold for Wound Healing. *ACS Appl. Mater. Interfaces* **2017**, *9*, 8556–8568. [CrossRef]
56. Shishatskaya, E.I.; Nikolaeva, E.D.; Vinogradova, O.N.; Volova, T.G. Experimental Wound Dressings of Degradable PHA for Skin Defect Repair. *J. Mater. Sci. Mater. Med.* **2016**, *27*, 165. [CrossRef]
57. Sharma, V.; Sehgal, R.; Gupta, R. Polyhydroxyalkanoate (PHA): Properties and Modifications. *Polymer* **2021**, *212*, 123161. [CrossRef]

58. Mohammed Gumel, A.; Aris, M.; Annuar, M.S. Modification of Polyhydroxyalkanoates (PHAs). *RSC Green Chem.* **2015**, *2015*, 141–182.
59. Anjum, A.; Zuber, M.; Zia, K.M.; Noreen, A.; Anjum, M.N.; Tabasum, S. Microbial Production of Polyhydroxyalkanoates (PHAs) and Its Copolymers: A Review of Recent Advancements. *Int. J. Biol. Macromol.* **2016**, *89*, 161–174. [CrossRef] [PubMed]
60. Puppi, D.; Pecorini, G.; Chiellini, F. Bioengineering Biomedical Processing of Polyhydroxyalkanoates. *Bioengineering* **2019**, *6*, 108. [CrossRef]
61. Kumar, V.; Sehgal, R.; Gupta, R. Blends and Composites of Polyhydroxyalkanoates (PHAs) and Their Applications. *Eur. Polym. J.* **2021**, *161*, 110824. [CrossRef]
62. Esmail, A.; Pereira, J.; Zoio, P.; Silvestre, S.; Menda, U.; Sevrin, C.; Grandfils, C.; Fortunato, E.; Reis, M.; Henriques, C.; et al. Oxygen Plasma Treated-Electrospun Polyhydroxyalkanoate Scaffolds for Hydrophilicity Improvement and Cell Adhesion. *Polymers* **2021**, *13*, 1056. [CrossRef]
63. Lopresti, F.; Liga, A.; Capuana, E.; Gulfi, D.; Zanca, C.; Inguanta, R.; Brucato, V.; la Carrubba, V.; Carfì Pavia, F. Effect of Polyhydroxyalkanoate (PHA) Concentration on Polymeric Scaffolds Based on Blends of Poly-L-Lactic Acid (PLLA) and PHA Prepared via Thermally Induced Phase Separation (TIPS). *Polymers* **2022**, *14*, 2494. [CrossRef] [PubMed]
64. Sashiwa, H.; Fukuda, R.; Okura, T.; Sato, S.; Nakayama, A. Microbial Degradation Behavior in Seawater of Polyester Blends Containing Poly(3-Hydroxybutyrate-Co-3-Hydroxyhexanoate) (PHBHHx). *Mar. Drugs* **2018**, *16*, 34. [CrossRef] [PubMed]
65. Carofiglio, V.E.; Stufano, P.; Cancelli, N.; de Benedictis, V.M.; Centrone, D.; de Benedetto, E.; Cataldo, A.; Sannino, A.; Demitri, C. Novel PHB/Olive Mill Wastewater Residue Composite Based Film: Thermal, Mechanical and Degradation Properties. *J. Environ. Chem. Eng.* **2017**, *5*, 6001–6007. [CrossRef]
66. Babaniyi, R.B.; Afolabi, F.J.; Obagunwa, M.P. Recycling of Used Polyethylene through Solvent Blending of Plasticized Polyhydroxybutyrate and Its Degradation Potential. *Compos. Part C Open Access* **2020**, *2*, 100021. [CrossRef]
67. Anjum, M.N.; Malik, S.A.; Bilal, C.H.; Rashid, U.; Nasif, M.; Mahmood Zia, K. Polyhydroxyalkanoates-Based Bionanocomposites. In *Bionanocomposites Green Synthesis and Applications*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 321–333. [CrossRef]
68. Liau, C.P.; bin Ahmad, M.; Shameli, K.; Yunus, W.M.Z.W.; Ibrahim, N.A.; Zainuddin, N.; Then, Y.Y. Preparation and Characterization of Polyhydroxybutyrate/Polycaprolactone Nanocomposites. *Sci. World J.* **2014**, *2014*, 572726. [CrossRef] [PubMed]
69. Jacquel, N.; Lo, C.-W.; Wei, Y.-H.; Wu, H.-S.; Wang, S.S. Isolation and Purification of Bacterial Poly(3-Hydroxyalkanoates). *Biochem. Eng. J.* **2008**, *39*, 15–27. [CrossRef]
70. Lizarraga-Valderrama, L.R.; Nigmatullin, R.; Ladino, B.; Taylor, C.S.; Boccaccini, A.R.; Knowles, J.C.; Claeyssens, F.; Haycock, J.W.; Roy, I. Modulation of Neuronal Cell Affinity of Composite Scaffolds Based on Polyhydroxyalkanoates and Bioactive Glasses. *Biomed. Mater.* **2020**, *15*, 045024. [CrossRef]
71. Choi, S.Y.; Cho, I.J.; Lee, Y.; Park, S.; Lee, S.Y. Biocatalytic Synthesis of Polylactate and Its Copolymers by Engineered Microorganisms. *Methods Enzymol.* **2019**, *627*, 125–162. [CrossRef]
72. Lizarraga-Valderrama, L.R.; Taylor, C.S.; Claeyssens, F.; Haycock, J.W.; Knowles, J.C.; Roy, I. Unidirectional Neuronal Cell Growth and Differentiation on Aligned Polyhydroxyalkanoate Blend Microfibres with Varying Diameters. *J. Tissue Eng. Regen. Med.* **2019**, *13*, 1581–1594. [CrossRef]
73. Madbouly, S.A. 8 Bio-Based Polyhydroxyalkanoates Blends and Composites. In *Biopolymers and Composites*; De Gruyter: Berlin, Germany, 2021; pp. 235–254.
74. Rai, R.; Boccaccini, A.R.; Knowles, J.C.; Mordon, N.; Salih, V.; Locke, I.C.; Moshrefi-Torbati, M.; Keshavarz, T.; Roy, I. The Homopolymer Poly(3-Hydroxyoctanoate) as a Matrix Material for Soft Tissue Engineering. *J. Appl. Polym. Sci.* **2011**, *122*, 3606–3617. [CrossRef]
75. Meng, W.; Xing, Z.C.; Jung, K.H.; Kim, S.Y.; Yuan, J.; Kang, I.K.; Yoon, S.C.; Shin, H.I. Synthesis of Gelatin-Containing PHBV Nanofiber Mats for Biomedical Application. *J. Mater. Sci. Mater. Med.* **2008**, *19*, 2799–2807. [CrossRef] [PubMed]
76. Grande, D.; Ramier, J.; Versace, D.L.; Renard, E.; Langlois, V. Design of Functionalized Biodegradable PHA-Based Electrospun Scaffolds Meant for Tissue Engineering Applications. *New Biotechnol.* **2017**, *37*, 129–137. [CrossRef] [PubMed]