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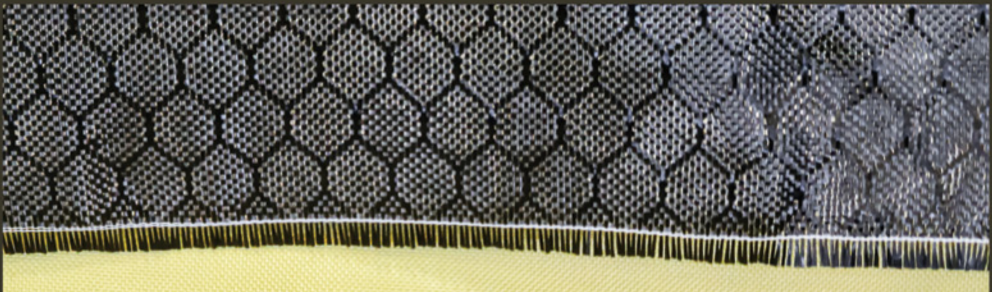

SMART BIOCOMPOSITE MATERIALS

FABRICATION, APPLICATIONS, AND SUSTAINABILITY

Edited by
MD. REZAUR RAHMAN
MUHAMMAD KHUSAIRY BIN BAKRI

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Smart Biocomposite Materials

The **Woodhead Publishing Series in Composites Science and Engineering** is a suite of professional reference books providing comprehensive coverage of recent developments in composite materials research for application now and in the future.

Woodhead Publishing Series in Composites Science and Engineering

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Fabrication, Applications, and Sustainability

Edited by

Md. Rezaur Rahman

Muhammad Khusairy Bin Bakri

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Dedication

This work is dedicated to my amazing wife and daughters, Shirin Akther, Fahriah Rahman, and Faizah Rahman, who are very special to me and made it possible for me to complete this work.

—Associate Professor Ts. Dr. Md. Rezaur Rahman

First, I would like to thank the Almighty God for the guidance, strength, power of mind, protection, and for giving us a healthy life. All of these we offer to you. Every difficult task needs self-effort as well as the guidance of elders, particularly those who are near to our hearts. I offer my humble dedications to my beautiful and loving father, mother, wife, and brothers, whose devotion, love, support, and nightly prayers have enabled me to work toward this significant achievement, along with all the dedicated, well-liked, and well-respected teachers and supervisors.

—Ts. Dr. Hj. Muhammad Khusairy Bin Bakri

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Preface

Materials science has now reached a critical phase of development, where combining sustainability, intelligence, and functionality is no longer visionary but the absolute requirement of the time. While the world is facing increasingly aggravated environmental concerns and its industries face growing demands for responsive and high-performance materials, the combination of biobased components with intelligent attributes is an opportunity for innovation, at the same time as it is eco-friendly and technologically advanced.

Intelligent biocomposite materials are one class of engineered systems combining renewable natural fibers with biodegradable or recyclable matrices and functional fillers or additives with responsive behaviors to external stimuli. These materials successfully address the imperative of reducing dependency on fossil-derived resources and possess enhanced features like self-healing, shape memory, and active sensing or actuation functions as well. The last 10 years have seen tremendous development in this field, driven by interdisciplinarity among materials engineering, biotechnology, polymer science, nanotechnology, and applied mechanics.

At the core of this discussion is a deep understanding of the interactions between different components, natural fibers, polymer matrices, and added functionalities. Advances in fabrication technologies, ranging from conventional compounding methods to advanced additive manufacturing methods, have enabled the large-scale production of biocomposites with tailored mechanical, thermal, and functional properties. The combination of responsive functionalities, such as sensors, stimuli-responsive fillers, or drug delivery systems, greatly expands their utility in high-end markets, such as biomedical devices, aerospace components, structural health monitoring, and soft robotics.

An important aspect of research in this area is mirroring the built-in self-sufficiency of nature with the development of materials with self-healing tendencies, the ability to change their shape in the presence of outside stimuli, and the ability to perform regulated-release functions. These attributes improve the potential of biocomposites and open up new prospects for research and application.

Sustainability remains the underlying tenet of this field, including not just the origin of materials but also life cycle assessment, recyclability, and environmental impact considerations. As the world economy increasingly moves toward more circular and biobased models of development, novel biocomposites are expected to play a key role in enabling this transformational process.

This book aims to act as a comprehensive scholarly reference for researchers, engineers, and postgraduate instructors to explore the scientific basis, processing methodologies, functional characteristics, and potential uses of intelligent biocomposite materials. This book integrates fundamental knowledge and state-of-the-art advancements to prompt further research and enable the development of advanced materials with features like intelligence, long-term performance, and sustainability.

Associate Professor Ts. Dr. Md. Rezaur Rahman
Ts. Dr. Hj. Muhammad Khusairy Bin Capt. Hj. Bakri

The role of polymer matrices and compositions

3

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3.1 Introduction

This chapter comprises a collection of data and information regarding the role of polymer matrices and compositions for biocomposite materials. The first half of this chapter covers the role of polymer matrices, where the categories of different polymer matrices are discussed, within the context of developing a biocomposite. The second half of this chapter covers the compositions of polymer matrices and its biocomposite, detailing a compilation of studies showcasing the different effects in weightage of matrices used, affecting the properties of the biocomposite, followed by the effects of weightage in reinforcement material, additives, and/or fillers. The differences in polymer matrices and composition used highly affect the outcome of the biocomposite being developed. Hence, the aim of this chapter is to showcase a collection of data and information for researchers developing a biocomposite material using polymer matrices.

3.2 Role of polymer matrices in polymer biocomposites

The use of polymer biocomposites is expanding in the material science world, with the desire to develop unique and tailored properties specific for varied desired applications. The role of polymer matrices in polymer biocomposites is significant when developing a biocomposite (Adamu et al., 2019; Asghari et al., 2017; Bakri et al., 2018; Fatema et al., 2024). The polymer matrices' roles include blending and binding reinforcement material together, forming a biocomposite. In addition, contributing to the biocomposites mechanical, chemical, thermal, biodegradability and physical properties (Hari et al., 2021; James et al., 2024; Jayamani et al., 2015, 2016; Jayamaui et al., 2020; Kuok et al., 2024; Lai et al., 2015; Namakka et al., 2024a,b; Namakka et al., 2023; Rahman et al., 2011). Hence, the importance of selecting the proper type of polymer matrices may determine the overall function of the biocomposite being developed. In our current times, it has been observed that there is a desire for more functional biodegradable materials from sustainable

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sources. This is greatly attributed to the development of sustainable technologies with biocomposites (Rajbanul Akhond & Sharif, 2022).

3.2.1 Types of polymer matrices

By definition, a conventional composite material is a multicomponent multiphase system mainly consist of a matrix material and reinforcement material (Wang et al., 2011). A biocomposite material, however, utilizes polymers that are biodegradable and or from a sustainable source. The polymer matrix (continuous phase) in biocomposites is mainly used to secure together the reinforcement material (disperse phase) and then cured into a solid piece of biocomposite. In addition, the role of polymer matrices in bicomposites also demonstrates the dispersion of applied forces throughout the bicomposites and the transfer of forces onto the reinforcement material. According to Saba et al. (2017), the polymer matrix affects the majority of the biocomposites' degradative characteristics and properties such as delamination, impact damage, chemical resistance, water absorption, and high temperature creep (Saba et al., 2017). Altering the type of polymer matrices and adding reinforcement material changes the interactions of the bonds which directly impact the overall performance of the biocomposite material (Wang et al., 2011).

3.2.1.1 Thermoset and thermoplastic matrices

Thermoset polymer matrices are typically in a viscous liquid state at room temperature, which can undergo a curing process with a hardening agent, forming an irreversible cross-linked solid structure (Kiew et al., 2013; Namakka et al., 2024a; Rahman et al., 2019; Rahman, Hamdan, Hasan, et al., 2015). In combination with adding reinforcement materials, the thermoset, fatigue strength with high thermal stability and chemical resistant properties (Rahman et al., 2013, 2017, 2024; Rahman, Hamdan, Hashim, et al., 2015; Sueraya et al., 2024). After successfully cured, the thermoset polymer matrix composite is irreversible, rendering it unable to be remolded with heat, in comparison to thermoplastic polymer matrices (Saba et al., 2015, 2017). Examples of conventional thermoset polymer matrices:

1 Polyester resin
2 Silicone
3 Melamine formaldehyde
4 Polyurethane
5 Epoxy resin
6 Urea formaldehyde

Thermoplastic polymer matrices are typically in a solid state at room temperature, which are known as feedstock in industrial terms, and can be in the form of pellets, sheets, or powder. Thermoplastic polymers' matrix physical properties are not easily altered during the melting, molding, and remolding process. In contrast to thermoset polymers, thermoplastics crosslinks are reversible and could be continued to be remolded via heat or melting process (Wanrosli et al., 2007). With the addition of reinforcement materials, thermoplastic polymer matrix composites are generally tougher, ductile, impact resistant, and damage tolerant in comparison to thermoset polymer matrix composites (Saba et al., 2015, 2017). Examples of conventional thermoplastic polymer matrices:

1. Polyethylene (PE)
2. Polypropylene (PP)
3. Polyvinyl chloride
4. Polystyrene
5. Acrylonitrile butadiene styrene
6. PE terephthalate
7. Polycarbonate
8. Polyamide
9. PE terephthalate glycol
10. Polymethyl methacrylate
11. Polyvinylidene fluoride
12. Polyoxymethylene
13. Polyimide
14. Polyphenylene sulfide

3.2.1.2 Elastomers matrices

Elastomer polymer matrices are known to have characteristics yielding high elasticity with the lack of plastic behavior. It has the capability of deforming and returning to its original shape. Uniquely, elastomer polymer matrices can act as a thermoset or thermoplastic polymer, depending on the type of elastomer and processing it undergoes (Paszkiewicz et al., 2017; Sousa, 2017). With the addition of reinforcement material, elastomer matrix composites can be tailored for various application that requires good tensile and flexural durability and impact resistance (Ahmadi et al., 2024). Some examples of elastomer matrices are:

1. Natural rubber
2. Polyurethane
3. Styrene-butadiene rubber
4. Nitrile rubber
5. Butyl rubber
6. Ethylene propylene diene monomer
7. Silicone rubber
8. Fluoroelastomers
9. Chloroprene rubber

3.2.2 Biodegradable natural and synthetic polymer matrices

The disposal of conventional plastic waste has serious consequences for the environment as the great majority of it are resistant to microbial degradation (Shivam, 2016). Hence, to solve part of this problem, researchers are now keen towards developing more biodegradable materials or biocomposite materials as alternative materials to conventional plastic materials (Jha et al., 2019). The development of biodegradable polymer matrices from natural and synthetic sources

Table 3.1 Classification examples of biodegradable polymer matrices.

Source	Derivatives
Natural biodegradable polymer	
Polysaccharides (carbohydrates)	Thermoplastic strach, cellulose and cellulose derivatives, chitin and chitosan, gums
Polypeptide (proteins)	Corn zein, wheat gluten, soy protein, collagen and gelatin, casein and caseinates, whey protein
Lipids, sugars, microorganisms	Polyhydroxyalkanoates Polyhydroxybutyrate Polyhydroxyvalerate Polyhydroxyoctanoate
Synthetic biodegradable polymer	
Aliphatic polyester (bio-derived monomers)	Polylactic acid Polyglycolic acid Polylactide-*co*-glycolide
Aliphatic polyester (synthetic monomers)	Polycaprolactone Polybutylene succinate Polybutylene succinate adipate Polyvinyl alcohol Polyvinyl acetate

with good biodegradability and mechanical properties is of most interest to many researchers.

In order for a composite to be categorized as a biocomposite, the polymer matrix must be biodegradable. The reinforcement material of a conventional composite material could be from natural fibers and other biodegradable material; however, the composite might not be able to biodegrade at a rate similar to a biocomposite using a biodegradable polymer matrix. In most cases, the polymer matrix has the biggest surface area directly exposed to the environment as compared to the reinforcement material. Hence, the role of a biodegradable polymer matrix is most important for the proper biodegradability of end-of-use biocomposites and environmental protection. The classification of biodegradable polymer matrices could be generally categorized according to their source material and synthesized derivatives (Jha et al., 2019). Table 3.1 showcases the classification examples of the source material and derivatives of natural and synthetic biodegradable polymer matrices (Samir et al., 2022).

3.2.2.1 Natural biodegradable polymer

The original source of natural biodegradable polymer is generally from biomass, which ranges from agricultural waste (i.e., wood, bamboo, corn, potato, cassava) and aquatic biomass (i.e., crustaceans, algae, kelp, seaweed) (Samir et al., 2022). Plant origin agricultural waste could yield different derivatives of the biodegradable polymer form of polysaccharides (i.e., cellulose, thermoplastic starches, and pectin) (Bassyouni et al., 2022; Maraveas, 2020; Samir et al., 2022).

Among the types of biodegradable polymers available, cellulose is a polysaccharide that is a long chain of carbohydrate molecules and is most commonly in abundance in nature as it is a major structural component of plant cell walls. The properties of cellulose and its derivatives are unique, as it is hydrophilic in nature and compatible with different materials. The cellulose affinity towards water allows the biodegrading process to occur; this is due to the moisture being absorbed, deteriorating the cellulose's mechanical properties. To ensure better stability and not deteriorate, researchers chemically modify cellulose to become different derivatives where reagents and OH molecule groups form bonds. These bonds improve the cellulose stability, solubility for biocomposite preparations, and improve its mechanical properties (Shah & Vasava, 2019).

Chitin is another polysaccharide that is abundant in nature in marine crustaceans (i.e., shells, crabs, and lobsters) and produced via fungal fermentation processes. The deacylated derivative of chitin is chitosan, which mostly could be extracted from arthropods' exoskeletons (Ghanbarzadeh & Almasi, 2013). The properties of chitin and the derivative chitosan are very promising, as they can be developed into a biodegradable polymer and biocomposite with high strength, good biodegradability, and nontoxic characteristics (Asghari, et al., 2016). Hence, it is currently in popular usage in the medical and pharmaceutical industries, tissue bioengineering, membrane barriers, cosmetics, and food industries (Asghari, et al., 2016; Luckachan & Pillai, 2011).

Synthesized via groups of microorganisms consuming agricultural waste media, the biodegradable polymer polyhydroxyalkanoates (PHAs) are naturally produced (Kumar & Thakur, 2017). PHAs are part of a biodegradable aliphatic polyester family, but in comparison to synthetic biodegradable polymers, PHAs are formed naturally and synthesized directly via microorganisms' metabolism (Soleymani Eil Bakhtiari et al., 2021; Tebaldi et al., 2019). PHAs are known to be biocompatible thermoplastics and could be utilized for the majority of agricultural wastes as a medium for the microorganism to metabolize. Additionally, it has the potential to be an alternative material for nonbiodegradable conventional polymers such as PE and PP (Samir et al., 2022).

3.2.2.2 Synthetic biodegradable polymer

Synthetic biodegradable polymer differs mostly from natural biodegradable polymer, simply from utilizing procedures of conventional polymerization (i.e., aliphatic polyesters, polylactide, aliphatic copolymer) (Mangaraj et al., 2019). The reduced degradation time and manufacturing process adaptability to industrial scale make synthetic biodegradable polymers a good alternative to conventional nonbiodegradable polymers. Examples of some of these synthetic biodegradable polymers are polylactic acid (PLA), polycaprolactone (PCL), and polybutylene succinate (PBS). Among these examples, PLA is one of the most popular researched synthetic biodegradable polymers(Jiang & Zhang, 2017; Luckachan & Pillai, 2011). PLA is a linear aliphatic polyester thermoplastic polymer synthesized from agricultural biomass, potato starch, wheat, rice, bran, and corn (Saini, 2017; Shah & Vasava, 2019). The processes of synthesizing PLA include polycondensation and ring-opening polymerization of lactic acid monomers (Luckachan & Pillai, 2011). It is noted that the final properties and high molecular weight are attained for PLA via the ring-opening polymerization method (Balla et al., 2021).

However, the mechanical, thermal, and biodegradable capabilities of PLA rely on the selection of stereoisomer distribution of the polymer chain. The application of the synthetic biodegradable polymer PLA ranges from biomedical applications due to its biocompatibility (Ramot et al., 2016) and is popularized as polymer spools for 3D-printing applications (Samir et al., 2022).

In cases of PCL and PBS, it is noted that both are also linear aliphatic thermoplastic polyesters but differ in synthesizing process. PCL is synthesized via ring-opening polymerization of caprolactone monomers with aluminum isopropoxide and tin octate catalyst, while PBS is synthesized via polycondensation of 1,4-butanediol with aliphatic dicarboxylic acid, succinic acid (Rafiqah et al., 2021; Saini, 2017; Samir et al., 2022). Most researchers study both polymers in terms of understanding the melting point state PCL (i.e., melting point between 58°C and 60°C) and PBS (i.e., melting point between 90°C and 120°C), manipulating them for developing into biocomposites, and degradation activity (i.e., level of crystallinity and molecular weight) (Ghanbarzadeh & Almasi, 2013; Rafiqah et al., 2021; Saini, 2017; Samir et al., 2022). Similar to PLA, the polymers are also used in biomedical applications, with additional pharmaceutical applications as long-term drug and vaccine delivery vehicles (Luckachan & Pillai, 2011; Samir et al., 2022).

3.3 Composition effect on polymer composite or biocomposite properties

The composition of a polymer composite or biocomposite refers to the polymer matrix and reinforcement mixture in terms of weightage (wt.%). Most researchers' attempt of developing the best polymer composite or biocomposite comes down to understanding the changes in properties when the wt.% of either polymer matrix or reinforcement is being altered. For simplicity, the majority of research maintain the wt.% for polymer matrices and only alter the wt.% of reinforcement used. Ideally, the alteration of wt.% leads to the optimal ratio which yields the best properties or a balance between cost, material usage and properties. To show examples of properties and wt.%, Table 3.2 showcases the examples of varied wt.% of reinforcement in polymer matrices for polymer composites and biocomposites and focuses on the best performing mechanical properties.

The composition such as the type of polymer matrices and reinforcement (wt.%) shows that an increase in wt.% does not equal to a direct improvement in mechanical properties; however within the range of wt.% tested by the researchers, an optimal wt.% range can be achieved for the best improvement in mechanical properties. In regard to developing a polymer composite or biocomposite, the best selection of

Table 3.2 The weightage (wt.%) range in relation to the best mechanical properties achieved by the studies.

Polymer matrix	Reinforcement	Weightage range	Best mechanical properties	References
Polypropylene (PE)	Sugarcane bagasse fiber	Range 5–20 wt.%, optimal wt.% is 20 wt.%	Tensile strength 22.3 ± 0.8 (MPa) Tensile modulus 1442.5 ± 68.7 (MPa) Flexural strength 37.2 ± 2.1 (MPa) Flexural modulus 1200.8 ± 112.9 (MPa)	Cerqueira et al. (2011)
High-density polypropylene (HDPE)	Yucca treculeana fibers	Range 10–30 wt.%, optimal wt.% is 20 wt.%	Tensile strength 31.18 ± 3.04 (MPa) Young modulus 2.25 ± 0.26 (MPa)	Ghernaout et al. (2024)
PVA	Nanocellulose	Range 2.5–10 wt.%, optimal wt.% is 5 wt.%	Linear PVA tensile strength ~50 kPa Cross-linked PVA tensile strength ~80 kPa	Mandal & Chakrabarty (2014)
PLA, PHBV	Nanocellulose	Range 5–15 wt.%, optimal wt.% is 15 wt.%	Hydrothermal effect (preconditioned) composites, PLA/PHBV (90:10 ratio) Tensile strength ~60 (MPa) Tensile modulus ~80 (MPa)	Bazan et al. (2024)
PVA	Cellulose microfibrils	Range 1–5 wt.%, optimal wt.% is 5 wt.%	Ultrasonication cellulose microfibril PVA composite Tensile Strength ~70 (MPa) Tensile modulus ~7000 (MPa)	Panaitescu et al. (2011)

(*Continued*)

Table 3.2 (Continued)

Polymer matrix	Reinforcement	Weightage range	Best mechanical properties	References
Epoxy	Woven carbon fiber fabric	Range 30–45 wt.%, Optimal wt.% is 35 wt.%	Tensile strength ~700 (MPa) Hardness value=45	Solomon et al. (2017)
Polypropylene (PE)	Polyoxyethylene (10) nonylphenyl ether (PNE) coated MFC, maleic anhydride (MAPP)	Range PP:MFC:MAPP (wt.%) 100:0:0 90:10:0 (optimal) 80:10:10 Optimal wt.% is 90:10:0	Noncoated 90:10:0 (wt.%) composite Tensile strength=1321 ±27 (MPa) Tensile modulus=24±0.1 (MPa)	Iwamoto et al. (2014)
NR	PALF, MWCNT	PALF wt.% range 10%–30%, added MWCNT maintained at 10 wt.% as separate sample i.e., (NR:PALF:MWCNT) Optimal wt.% is 100:30:10	Tensile strength (stress–strain curves) ~ 1.9 (MPa) Hardness value=62.8 Shore A	Yi Xuan et al. (2024)
Regenerated cellulose	Recycled denim fabrics	Cellulose dissolution range 6 wt.% (optimal) shows best for the all-cellulose composite laminate sample	Tensile strength ~ 29 (MPa) Flexural modulus ~ 2.1 (MPa) Impact strength ~ 27 (kJ/m^2)	Baghaei et al. (2020)
Nylon PA6	Glass fiber	Range 5–20 wt.%, optimal wt.% is 20 wt.%	Tensile strength=57.8 (MPa) Tensile modulus=2.26 (GPa) Fracture stress=68.8 (MPa)	Nuruzzaman et al. (2016)

MFC, Microfibrillated cellulose; *MWCNT*, multiwalled carbon nanotube; *NR*, natural rubber; *PALF*, pineapple leaf fiber; *PHBV*, poly(3-hydroxybutyrate-*co*-3-hydroxyvalerate); *PLA*, polylactic acid; *PVA*, polyvinyl alcohol.

polymer matrices typically depends on the desired properties and application. Hence, the optimal wt.% is selected best fit to what is the desired performance or properties require for the desired application. The main properties of the polymer matrices serve as the baseline properties before the addition of reinforcements, which improve or add new properties (i.e., electrical conductivity, thermal resistance, hardness, mechanical strength, and improve biodegradation effect).

3.3.1 Polymer in smart composite materials

The class of smart polymer composite materials involves a specific type of polymer composite material that has the ability to react to environmental stimulus or stimuli. Current research shows potential smart polymer composite materials reacting to temperature, moisture or humidity, pressure, mechanical stresses, electrical conductivity, and optical changes (Bi & Huang, 2022; Sahayaraj et al., 2023).

Some examples of current applications of smart polymer composite materials include materials with the ability of either shape memory, electrical conductivity, and self-healing properties. Shape memory polymer composites have the ability to deform and return to its original shape. Examples of shape memory polymer matrices include polyurethane, PCL, polyvinyl alcohol, and PE. Environmental stimuli such as fluctuating temperature, humidity, pressure, and stress can trigger deformation of shape memory polymer composites. The fluctuation of transition temperature or pressure influences the material's pliability, for example, a malleable state and maintaining its initial state prior to experiencing deformation (Sahayaraj et al., 2023).

To regulate the transition temperature or pressure of shape memory polymer composites, the implementation of different polymers or shape memory agents, plasticizers, and cross-linking agents may be advantageous. As each material change may yield different properties, further research is required to properly develop a shape memory polymer composite for specific applications. The potential application of shape memory polymer composites is case dependent, for example, medical instruments such as stents and catheters. The shape memory polymer composites could be use by inserting it into the body at a flexible malleable state and then reverted to its original shape to accomplish the task at hand (Sahayaraj et al., 2023; Wang et al., 2022).

The ability of conductive polymer composite materials to conduct electricity is based accordingly to the increased conductive properties due to the incorporation of fillers, for example, metals or carbon-based materials mixed into the polymer matrix. The polymer matrices (e.g., polyaniline, polypyrrole, polythiophene, polyacetylene) do have a certain level of electrical conductivity, which varies from 10^{-3} to 10^{5} S/cm (Sahayaraj et al., 2023). The electrical conductivity of the polymer matrices are low in comparison to metals and carbon-based materials; however, they are useful for applications in electronics, batteries, and sensors (Sahayaraj et al., 2023; Wang et al., 2021).

Self-healing polymer composite materials have the ability to self-repair its structure after damage has occurred. The act of self-healing is accomplished mainly due to the incorporation of a self-healing mechanism. The presence of microencapsulated healing agents or the formation of covalent bonds between polymer chains are attributing to the self-healing mechanism of the polymer composite materials (Tan et al., 2019).

Microencapsulated healing agents are micro-sized solid particles or droplets of liquids sealed in inert capsules to separate and shield from environmental effects. A combination of catalyst, monomer polymerization, coating, healing time, and quality of the microcapsule contributes to the performance of the resulting act of healing the damaged polymer composite structure (Paladugu et al., 2022). These self-healing materials are generally specially prepared composite materials and currently do not have a pure polymer matrix that exhibits such self-healing properties. Self-healing polymer composite materials could reach healing efficiency of up to 95% depending on the type of polymer, self-healing agent, and preparation methods (Xu et al., 2023).

3.4 Summary

In summary, this chapter covers the role of polymer matrices related to the types of polymers (i.e., conventional and biodegradable polymer matrices) and compositions in terms of weightage between polymer matrices and reinforcement material. The polymer matrices' roles include blending and binding reinforcement material as a composite material and also contributing to the initial main properties. Biocomposites are simply polymer composites with both matrix and reinforcement being more biodegradable compared to conventional polymer composites. Compositions related to weightage (wt.%) allow the understanding of modifying properties via altering matrix and reinforcement weightages (wt.%). The optimal weightages (wt.%) yield from altering weightages (wt.%) of either polymer matrices and reinforcements, hence resulting in attaining unique and desired properties for the desired applications.

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