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Effect of Composite Technologies on the Mechanical Properties and Biodegradability of Agricultural Polymeric Materials

Nor Syahidah Md Sam[1,2]*, Ganisan Krishnen[2], Norfhairna Baharulrazi[1], Luqman Chuah Abdullah[3] and Rohah Abdul Majid[1]

[1]Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia

[2]Soil Science, Water and Fertilizer Research Centre, Malaysian Agricultural Research and Development Institute (MARDI), MARDI Headquarters, 43400 Serdang, Malaysia

[3]Department of Chemical and Environmental Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

ABSTRACT

Polymeric materials are widely applied in agriculture for purposes such as weed control, nutrient delivery, and the controlled release of pesticides and herbicides. However, their environmental impact, particularly from synthetic polymers like polyethylene and polystyrene, stems from their resistance to degradation. With an estimated 80% of global plastic waste accumulating in ecosystems or landfills, the development of biodegradable alternatives has become a critical concern. This has led to a growing demand for biodegradable polymers in applications such as plastic mulching and controlled-release systems, aiming to reduce pollution, support soil health and ease post-harvest residue management. This paper provides an overview of recent developments in biodegradable polymer composites, with a focus on how composite technologies enhance both the mechanical performance and biodegradability of these materials. It also provides an overview of the growing recognition of polymer composites for their role in improving the efficiency and precision of nutrient, pesticide, and herbicide delivery to plants, minimizing environmental losses and enhancing resource use. The discussion emphasizes the need for biodegradable polymers to meet functional criteria similar to synthetic plastics, such as adequate tensile strength and elongation while remaining capable of degrading under agricultural conditions. The integration of fillers, reinforcements, and polymer blends has shown promise in improving durability during

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E-mail address:
nor86@graduate.utm.my (Nor Syahidah Md Sam)
ganisan@mardi.gov.my (Ganisan Krishnen)
norfhairna@utm.my (Norfhairna Baharulrazi)
chuah@upm.edu.my (Luqman Chuah Abdullah)
r-rohah@utm.my (Rohah Abdul Majid)
*Corresponding author

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use and facilitating breakdown afterward. Such dual performance is vital for sustainable agricultural systems. This review aims to offer insights into the role of composite technologies in advancing biodegradable polymer materials for agriculture, supporting both efficient input delivery and long-term environmental compatibility.

Keywords: Biodegradable polymer, controlled release system, degradation

INTRODUCTION

Polymeric materials are frequently utilized in agriculture for weed control, controlled release of agricultural active agents such as herbicides and pesticides, and controlled release of fertilizers (Sikder et al., 2021). The use of synthetic polymers, such as polystyrene, polyvinyl chloride, and polyethylene, has an environmental impact due to their delayed or non-degradable nature (Kiselev et al., 2021). According to Geyer et al. (2017), a significant amount of plastic waste, approximately 80%, is currently estimated to be present in natural ecosystems or landfills. As a result, it is critical to convert it to a biodegradable polymer that can biodegrade in the soil. They must exhibit adequate mechanical properties to withstand agricultural operations while degrading within a defined timeframe to release environmentally safe byproducts, such as CO_2 and H_2O. For instance, in agricultural mulches, the degradation period should align with crop cycles, and the byproducts must not hinder soil health.

Aside from biodegradability, the mechanical properties of the manufactured biodegradable polymers must meet synthetic polymer standards. For example, the tensile characteristics and elongation at the break of mulching are critical in ensuring that the plastic is not torn or broken during mulching preparation (Merino et al., 2022). Other than that, controlled-release fertilizers (CRFs) allow nutrients to be released gradually or in stages, which can be optimized to coincide with the timing of nutrient requirements during crop growth, potentially saving labor costs (Vejan et al., 2021). Therefore, researchers and industry players have extensively researched the use of fillers, reinforcements, or other polymers to improve the characteristics and biodegradability of agricultural polymeric materials.

Fitriani et al. (2025) developed a hybrid biodegradable film composed of whey protein isolate, polyvinyl alcohol, and cellulose nanocrystals derived from pineapple crown leaves, utilizing optimal concentrations determined in prior research. The results demonstrate that incorporating PVA and CNC into the WPI matrix enhances the mechanical, physicochemical, morphological, and thermal properties of the resulting hybrid film. PBAT/PLA-PPC-PTLA ternary blend polymer composites, incorporating polybutylene adipate-co-terephthalate, polylactic acid, polypropylene carbonate, and a lactic acid-isopropyl carbonate copolymer, have shown promise in recent studies for agricultural applications.

These composites exhibit improved tensile strength and water vapor barrier properties, along with a comparable biodegradation rate (Guo et al., 2024).

The present review aims to look into various fillers or reinforcement agents utilized in the production of biodegradable polymer composites and their influence on the mechanical characteristics and biodegradability of polymeric materials. The discussion will also encompass polymer composites and their function in regulating the release of pesticides, herbicides, and nutrients. We believe that this brief overview provides a vital insight into the importance of polymeric composites in improving the mechanical characteristics, release characteristics and biodegradability of polymers while being ecologically benign.

BIODEGRADATION

The definition of biodegradation varies depending on the specific domain of application of the polymers, whether it be in the biomedical or natural environment. Numerous discrete definitions have been formally established, as per the historical records of standard-setting entities and their corresponding interests. According to the definition provided by Albertsson and Karlsson (2002), biodegradation is a phenomenon that entails the enzymatic and/or chemical breakdown of living organisms and their excretions. It is imperative to take into account abiotic reactions, including photodegradation, hydrolysis, and oxidation, as they have the potential to alter the polymer before, during, or instead of biodegradation as a result of environmental influences. The process of polymer biodegradation is characterized by the degradation of its chemical and physical properties, resulting in a reduction in its molecular mass and the production of low-molecular-weight products, such as CO_2, CH_4, and H_2O. This process is facilitated by microorganisms in both aerobic and anaerobic conditions, as well as abiotic chemical reactions such as photodegradation, hydrolysis, and oxidation (Luckachan & Pillai, 2011).

Several biopolymers have been designed to be biodegradable in soil, landfills, or composting facilities. The process of material degradation is dependent on the existence of specific microorganisms. The requirement of indigenous soil microorganisms and moisture is commonly essential, thereby enhancing the appeal of microbially degraded plastics (Kasirajan & Ngouajio, 2012).

Biodegradation Process

Biodegradation is the only degradation mechanism that is capable of completely removing a polymer or its breakdown byproducts from the environment. The process of biodegradation occurs in a dual-phase manner. The initial step involves the depolymerization of the macromolecules, resulting in the formation of shorter chains (Figure 1). Typically, this particular stage takes place extracellularly owing to the considerable size of the polymer chain and the insolubility of numerous polymers. Polymeric chain cleavage is attributed to

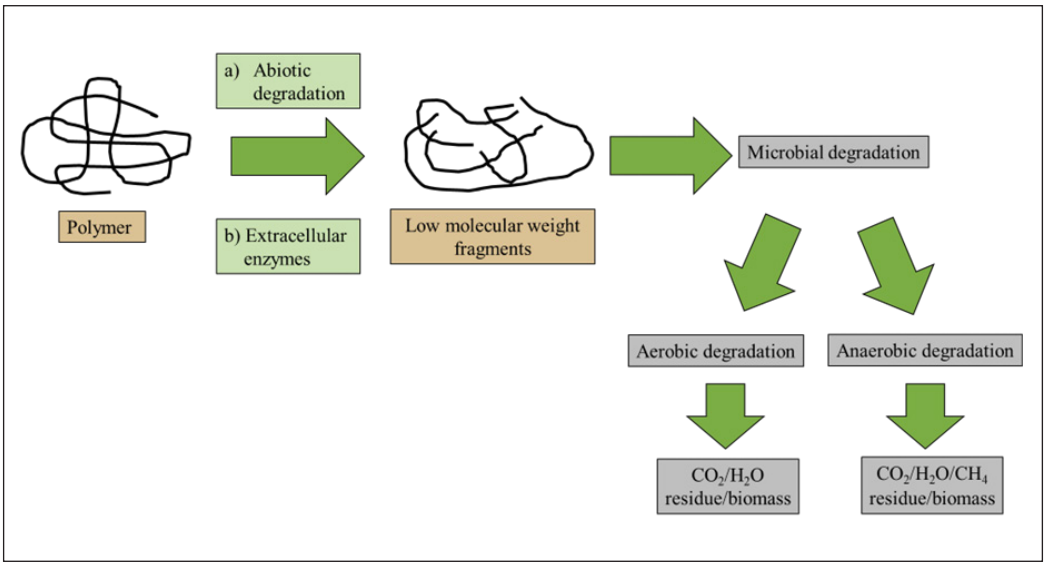

Figure 1. A diagrammatic illustration of biodegradation's chemistry (Luckachan & Pillai, 2011)

extracellular enzymes, including endo- and exo-enzymes, as well as abiotic reactions. In this phase, there is an increase in the contact area between the polymer and the microorganism (Luckachan & Pillai, 2011)

The subsequent stage relates to mineralization. Upon reaching a diminutive size, oligomeric fragments undergo cellular transportation and subsequent bioassimilation by microorganisms, ultimately leading to mineralization. Biodegradation occurs under distinct conditions, depending on the presence or absence of oxygen: aerobic biodegradation occurs in the presence of oxygen, while anaerobic biodegradation occurs in the absence of oxygen. Complete biodegradation or mineralization is achieved when there is no residual matter left, signifying that the initial product has been fully transformed into gaseous byproducts and salts.

The presence of weak links within a chain can facilitate attacks by specific microorganisms. The major chains of polyolefin and vinyl groups include carbon atoms, making them resistant to breakdown and biodegradation. Biodegradable polyesters such as poly(hydroxyalkanoates), adipate/terephthalate, and polylactic acid are hydrolyzed due to ester linkages. Hydrolysis non-specifically cleaves the primary polymer chain, reducing molecular weight. Smaller molecules are more vulnerable to enzymatic processes, accelerating biodegradation. Thus, chemical composition determines a polymer's biodegradability and erosion process (Kasirajan & Ngouajio, 2012). Some polymers and their biodegradability are presented in Table 1.

Table 1
Polymers and their biodegradability

Polymer	Biodegradability	Notes	References
Low-density polyethylene (LDPE)	No	Commercially available mulch	Hussain & Hamid, 2003
Linear low-density polyethylene (LLDPE)	No	Commercially available mulch	Espi, 2006
Ethylene-vinyl acetate (EVA)	No	Commercially available mulch	Espi, 2006
Ethylene butyl acrylate (EBA)	No	Commercially available mulch	Espi, 2006
Blends of LDPE, or LLDPE, with EVA	No	Commercially available mulch	Amin, 2001
Poly(butylene adipate-co-terephthalate)	Yes	60% after 45 days.	Kijchavengkul et al., 2008
PBAT			Kijchavengkul et al., 2008
Cellulose		100% after 45 days	
Polylactide or polylactic acid (PLA) with spinach stem	Yes	38% after 6 months	Merino et al., 2022
Polyhydroxybutyrate (PHB)	Yes	62% after 6 weeks	Altaee et al., 2016
Copolymer of PCL and starch	Yes	88% after 44 days under aerobic conditions	Cho et al., 2011
Ramie and cotton fiber/starch film	Yes	53.7% after 30 days	Tan et al., 2016
Ramie and cotton fiber/ polyvinyl alcohol film	Yes	79.2% after 45 days	Tan et al., 2016
Ramie and cotton fiber/ polyacrylate	Yes	16.0% after 30 days	Tan et al., 2016

COMPOSITE MATERIAL

Composite materials are assemblies of two or more materials that result in a final product with properties that surpass those of individual constituent materials (Hsissou et al., 2019; Khalil et al., 2012). These materials consist of a matrix that contains embedded materials, maintaining the cohesion and orientation of the load. The matrix can transmit stresses to the load, exhibiting high degrees of heterogeneity and often possessing anisotropic properties. Composite materials can be categorized into organic, mineral, and metallic categories based on the matrix nature (Hsissou et al., 2021). Organic composites include cardboard, reinforced plastics, and laminated tires. Mineral composites include carbon-carbon composites, concrete, and ceramic composites. Metallic composites are composed of aluminum/boron fibers and aluminum/carbon fibers. The final category comprises

metallic composites, which are composed of aluminum/boron and aluminum/carbon fibers (Hsissou et al., 2021). Composite materials have a significant impact on various fields of application, including packaging, biomedicine, lightweight structures, civil engineering, thermomechanical components, and the automotive, aviation, sports, and aerospace industries. The matrix nature, charge shape and proportion, interface quality, and production process all impact the properties of composite materials.

Biodegradable Polymers Composites

The development of composites and nanocomposites has revolutionized materials science, with biodegradable polymer matrices being crucial for their advancement (Bortolin et al., 2013; Giroto et al., 2014). Natural fiber eco-composites are a rapidly emerging product, and renewable, biodegradable polymers such as cellulosic plastics, corn-based plastics, and polyhydroxyalkanoates can be utilized in nanocomposites for various applications (Kiselev et al., 2021; Stasi et al., 2020) . These nanocomposites will exhibit enhanced strength, stiffness, toughness, reduced permeability, reduced thermal expansion, and elevated heat deflection temperature. Green, lightweight nanocomposite materials are expected to supplant conventional petroleum-based composites.

The incorporation of biodegradable natural fibers as reinforcement in natural polymer composites represents a new development. The use of natural polymer-based packaging materials is limited due to their low mechanical properties and low water resistance. However, these inherent shortcomings can be addressed by utilizing nanocomposite technology. For example, the packaging properties of natural biopolymer-layered silicate nanocomposites are significantly enhanced owing to their uniform dispersion at the nanometer scale. The mentioned improvements pertain to enhanced modulus and strength, reduced gas permeability, and improved water resistance (Rhim & Ng, 2007).

Polymer composites play a vital role in enhancing the mechanical properties and biodegradability of materials used in agriculture. Several approaches utilize natural fillers and synthetic polymers to achieve this. Polyvinyl alcohol composites, for example, are created through casting methods, incorporating fillers like starch (Wang et al., 2017) and natural fibers derived from agricultural waste such as sugarcane bagasse, apple pomace, and orange peels (Chiellini et al., 2001) and cellulose nanocrystals derived from pineapple crown leaves (Fitriani et al., 2025). Similarly, poly(butylene succinate) composites are manufactured using hot-pressing techniques with starch as a filler, resulting in biodegradable materials (Flores et al., 2009).

Further innovations include mango seed starch matrices reinforced with kraft pulp microfibrillated cellulose for enhanced performance and chemically modified maize starch combined with a lignin filler to improve structural integrity (Patil & Netravali, 2016; Spiridon et al., 2011). Thermoplastic maize starch composites utilize carbon ash

from agricultural waste, thereby expanding their applications in sustainable materials (Stasi et al., 2020). Tapioca starch/PBS composites are reinforced with empty fruit bunch fibers, providing an eco-friendly option (Ayu et al., 2020). Polylactic acid composites are developed with fillers like Osage orange wood fibers, processed into films with varying fiber sizes and weights, and also with vegetable wastes such as spinach stems, tomato pomace, and cocoa shells, blended with epoxidized soybean oil methyl ester for enhanced properties (Finkenstadt & Tisserat, 2010; Merino et al., 2022). Furthermore, polyvinyl alcohol/starch composites incorporate halloysite nanotubes for improved functionality in specific agricultural applications (Zeng et al., 2019). Controlled-release fertilizer coatings are manufactured using various polymer matrices, including polyurethane and starch-based composites, combined with fillers like montmorillonite, bentonite, cellulose, and chitosan to enhance efficiency and sustainability (Liao et al., 2021). These diverse polymer composites demonstrate the innovative use of fillers to meet the demands of modern agriculture while promoting environmental responsibility. Through various production methods, they contribute to advancements in mulches, controlled-release herbicides and pesticides, and other biodegradable agricultural products.

Clay

Polymer nanocomposites are created through the use of intercalation chemistry involving layered inorganic solids. These solids may include graphite, clay minerals, transition metal dichalcogenides, metal phosphates, phosphonates, and layered double hydroxides. The unique structure and characteristics of clay minerals, such as montmorillonite, hectorite, and saponite, have led to their widespread use. Minerals can be classified into three distinct groups, namely the 2:1 type, the 1:1 type, and the layered silicic acids. The 2:1 clay belongs to the smectite family and is composed of thin plates that are only a few nanometers thick. These plates are made up of sheets of aluminum octahedrons that are sandwiched between two sheets of silicon tetrahedrons. The neutralization of the van der Waals gap is achieved by the exchangeable metal cations present due to the arrangement of layers. The 1:1 type is composed of alternating layers of aluminum octahedrons and silicon tetrahedrons. The bonding between the layers is maintained by hydrogen bonding (Zeng et al., 2005).

Layered silicic acids are composed of silicon tetrahedron sheets with varying layer thicknesses, with a fundamental architecture consisting of stratified silicate frameworks and intercalated hydrated alkali metal cations. The presence of silanol groups within the interlayer regions facilitates organic modification through the grafting of functional groups onto the regions (Zeng et al., 2005).

The presence of clay minerals is crucial in polymer nanocomposites owing to their intricate intercalation chemistry, remarkable strength and stiffness, and the aspect ratio of individual platelets. Due to their distinctive layered structure and remarkable intercalation capabilities, they can undergo chemical modification to achieve compatibility with polymers

(Figure 3). Modifications such as organic surface treatments (e.g., with organic cations or silanes) enhance their compatibility with polymer matrices. These modifications enable improved dispersion and mechanical properties, particularly tensile strength and stiffness. For example, montmorillonite (MMT) nanocomposites have been used in agricultural mulches and controlled-release fertilizers, offering both enhanced tensile properties and slower nutrient release (Wang et al., 2017). A simple diagram illustrating the layered structure of clay minerals and their cation exchange process is included in Figure 2 to aid comprehension.

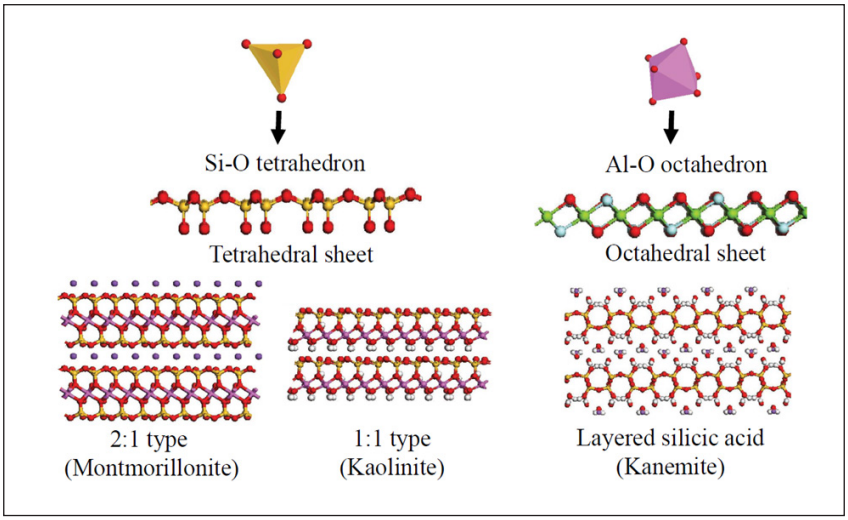

Figure 2. The structure of montmorillonite, kaolinite, and kanemite clay minerals. Combinations of tetrahedral and octahedral sheets, whose fundamental elements are typically Si-O octahedron, are used to construct them (Zeng et al., 2005)

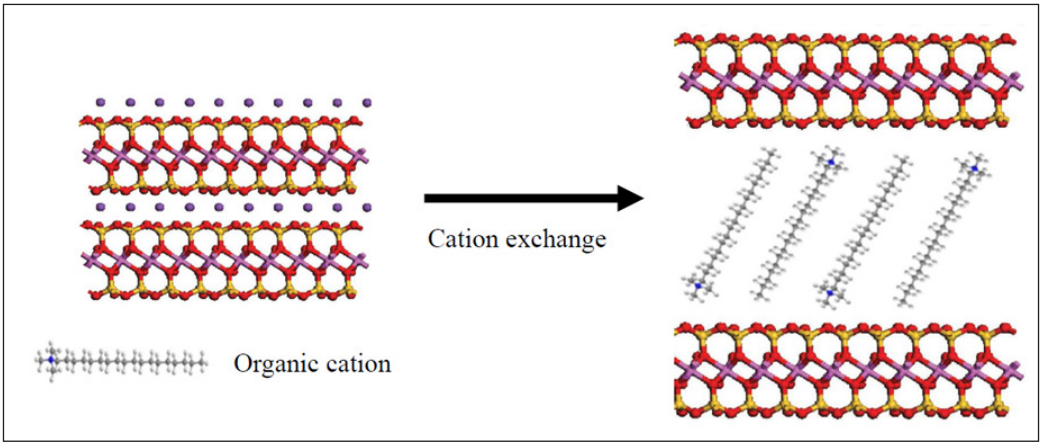

Figure 3. Schematic illustration of organo-modification of montmorillonite by organic cation

Smectite clays, such as MMT and hectorite, have the ability to undergo exfoliation or delamination, resulting in the formation of nanometer platelets. These platelets have a thickness of 1 nm, a surface area of 700 to 800 m^2/g and an aspect ratio ranging from 100 to 1500. Platelets exhibit exceptional strength and rigidity, rendering them rigid inorganic polymers (Zeng et al., 2005).

Organic Fillers

Organic fillers are composed of organic substances, including cellulose fibers, wood flour, fruit bark flour, vegetable fibers, and starches. The utilization of cellulose fillers is common in thermosetting resins such as aminoplasts and phenoplasts. This is primarily due to their low density and low cost. The addition of wood flour to a material can improve its impact resistance, shrinkage, and dimensional stability. On the other hand, fruit bark flour is commonly incorporated into thermoplastic matrices such as ABS and polypropylene. Cellulose is the primary component of vegetable fibers, which exhibit high mechanical strength and low density. Starches are a type of carbohydrate that is present in plants. They come in different sizes and configurations and are utilized as fillers in plastics to regulate their biodegradability (Hsissou et al., 2021).

Natural fibers have been used in composites since the 1970s, with cellulose fiber-reinforced polymer composites gaining interest in various industries. These composites exhibit high specific tensile strength and stiffness, making them lightweight alternatives to traditional reinforcements, such as glass fibers. They are less hazardous to handle and require less energy during processing. Natural fibers sequester carbon dioxide during growth and are biodegradable. However, due to different growing conditions, natural fibers often show a large scatter of properties compared to industrially made glass fibers. Strong quality management and extreme care are necessary for reliable and reproducible results (Huber et al., 2012).

Cellulose

Cellulose is a versatile biopolymer with numerous applications, including reinforcing components in biocomposites and as a renewable and biodegradable raw material. It is composed of d-anhydroglucopyranose units $(C_6H_{11})_5$/IUPAC, which are glucose units assembled into groups of two called "cellobiose" units. Cellulose microfibrils, found in plants' secondary cell walls, exhibit crystalline, paracrystalline, and amorphous regions. The degree of polymerization (DP) of cellulose varies depending on the source, with wood fibers having a higher degree of polymerization (300) and plant fibers and bacterial cellulose having a higher degree of polymerization (10,000). Cellulose microfibrils can be classified as nanomaterials due to their lateral dimensions of 5–50 nm. The mechanical properties of cellulose compete well with other engineering materials like aluminum and

glass fibers, with the specific stiffness of native cellulose being among the highest among all natural materials (Huber et al., 2012).

Halloysite Nanotubes

Halloysite nanotubes (HNTs) have garnered significant interest from the scientific community, both experimentally and theoretically, in recent times (Liu et al., 2014; Yuan et al., 2012, 2015). HNTs are a multilayered nanotubular structure with a structural formula of $Al_2(OH)_4Si_2O_5.nH_2O$ (Figure 4). They belong to the kaolin group of natural aluminum silicate minerals and have a range of dimensions, including 0.5–2 μm lengths and occasionally exceeding 30 um. HNTs are used as adsorbent materials for the controlled release of active molecules due to their biocompatibility and tubular structure (Huang et al., 2017; Zeng et al., 2019).

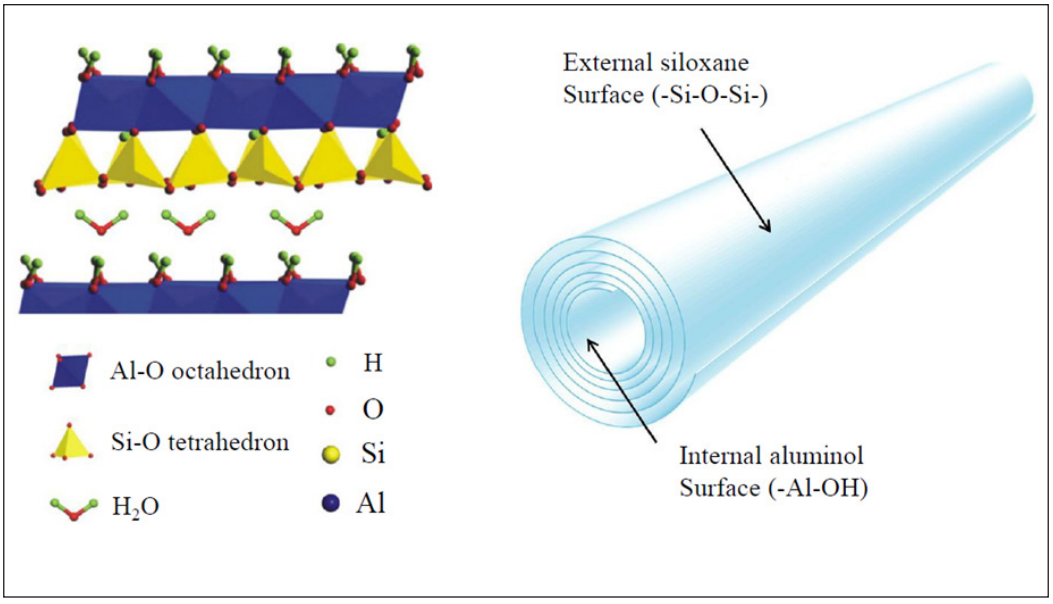

Figure 4. Structure and chemistry of halloysite nanotubes

BIODEGRADABLE COMPOSITES FOR CONTROLLED-RELEASE HERBICIDES AND PESTICIDES

Agrochemicals, such as fertilizers, herbicides, and pesticides, are essential for modern agriculture but often have unfavorable environmental consequences, such as bioaccumulation within the food web and pollution of ecosystems. Integrating functional polymers with agrochemicals can achieve the controlled release of active ingredients over extended periods, thereby minimizing the risk of environmental contamination.

This approach can mitigate degradation, evaporation, and washout processes, increasing efficacy while decreasing environmental toxicity. The optimal delivery systems for sustainable agriculture should ensure regulated release, protection from deteriorating factors, reduced cytotoxicity, and prolonged durability of nanocarriers. These features minimize pesticide application and treatment frequency, extending the validity period. (Sikder et al., 2021).

The addition of fillers and enforcement agents, such as bentonite clay, montmorillonite, and kaolinite, has enhanced the nutrient-release properties of the agricultural active agent. Nisar et al. (2009) developed coatings composed of polymers and clay that incorporate azadirachtin A to preserve the quality of soybean seeds during storage. The carriers employed in the study included ethyl cellulose, methylcellulose, gum acacia, gum tragacanth, rosin, hydroxyethyl cellulose, polyethyl methacrylate, polyethylene glycol, polyvinyl chloride, polyvinyl pyrrolidone, polyvinyl acetate, Agrimer VA 6 polymers, and bentonite clay. The study found that azadirachtin-A has a 50% discharge duration of 8.02 to 21.36 hours in aqueous solutions. The half-life of the substance in seed coats ranged from 4.37 to 11.22 months, while in azadirachtin-A WP, it was 3.45 months. The coats functioned as a barrier against moisture, decreasing azadirachtin A degradation and hindering fungi growth. Polyvinyl acetate, polyethyl methacrylate, and polyvinyl pyrrolidone showed higher superiority. The study found a significant positive association between azadirachtin A and seed germination and vigor, while a negative correlation was observed between azadirachtin A and moisture content.

Additionally, Kumar et al. (2010) conducted a study on the development of controlled-release formulations for the insecticide cartap hydrochloride. This was achieved through the utilization of commercially available materials such as carboxymethyl cellulose and polyvinylchloride (emulsion and suspension), in combination with clays such as kaolinite, bentonite, and fuller's earth. The formulation consisting of sodium carboxymethyl cellulose, cartap hydrochloride, and kaolinite exhibited exceptional efficacy (3.33%) in managing rice leaf folders in rice (Oryza sativa L.) cultivated in open fields.

Giroto et al. (2014) developed a host system consisting of starch gel, a biodegradable polymer, and montmorillonite clay (MMT) for slow-release delivery of hydrophobic herbicides. The nanocomposite structure regulates the release of the active compound by imposing diffusional barriers. The nanocomposites retained more herbicide than pure samples, indicating a cooperative or synergistic effect between the constituents. Biodegradation tests showed extended biodegradation periods for the nanocomposite compared to pure materials. The release behavior was governed by the interaction between the constituents, even at extremely high concentrations of the herbicide. The

study examined the impact of MMT incorporation on the biodegradation of starch gel and ametryne. The initial period showed similar degradation extension across various samples, but a noticeable contrast was observed after a 20-day composting period. The biodegradation of ametryne and starch was hindered by the addition of MMT, as evidenced by higher levels of CO_2 evolution in the absence of MMT compared to the levels in the St/MMT 1:1, 1:1:2, 1:2:3, and 1:4:5 Amet nanocomposites. This occurrence can be attributed to a possible van der Waals interaction between starch and ametryne, as well as clay and ametryne, as evidenced by FTIR findings.

Li et al. (2011) studied the efficacy of an amphiphilic chitosan-poly(lactide) graft copolymer, where poly(lactide) was grafted onto the water-soluble chitosan to improve insecticide loading. The submicron nanoparticles, which were formed by the amphiphilic polymer, exhibited the ability to encapsulate imidacloprid and provide a sustained release profile. In a subsequent study, the identical nanocarrier was employed as a delivery system for fungicide, specifically flusilazole, which was incorporated into the polymeric micelles using a modified nanoprecipitation technique (Mei et al., 2014). According to the authors' report, the mechanism of flusilazole release involved diffusion through the polymer matrix. Additionally, the utilization of nanoparticles was found to be effective in augmenting the activity of flusilazole by facilitating improved penetration through grape leaves.

Another key factor in the design of controlled-release formulations is the consideration of the mechanical properties and biodegradability of the delivery system. Mechanical properties, such as tensile strength, flexibility, and durability, play a crucial role in the controlled release of active ingredients, ensuring that the formulation can withstand the stresses encountered during application and storage and release the compounds at the desired rate and location. Biodegradability, on the other hand, is essential for minimizing the environmental impact of the delivery system, as it allows the formulation to degrade over time, reducing the persistence of the active ingredients in the environment (Dhaliwal, 2018).

The importance of mechanical properties and biodegradability in the development of controlled-release formulations for pesticides and herbicides cannot be overstated. By considering these factors, researchers can develop innovative solutions that mitigate the environmental impact of these chemicals while maintaining their efficacy, ultimately contributing to more sustainable agricultural practices.

Wang and his coworkers have prepared a controlled-release pesticide using a polyvinyl alcohol starch composite with sodium montmorillonite and alginate crosslinked structures (Wang et al., 2017). The herbicide 2,4-dichlorophenoxyacetic acid (2,4-D) as

a model drug was incorporated into sodium montmorillonite (Na-MMT) and an alginate ion-crosslinking structure. The result showed that the incorporation of Na-MMT and alginate ion crosslinking structure into the composite polymer significantly reduces the release rate of the model drug. In addition, it was able to sustain the release of the model drug for an extended duration. Experiments involving diffusion through the soil layer revealed that both composite polymers possessed excellent release characteristics. After eight irrigations, the total quantity of leached herbicide 2,4-D decreased from 100% to 57.6%. Additionally, the film exhibited advantageous thermal and mechanical properties, and it is anticipated to have applications in agriculture and other disciplines.

Zeng et al. (2019) have utilized Halloysite nanotubes (HNTs) to load the botanical herbicide that is an active ingredient of Eupatorium adenophora Spreng (AIEAS). Furthermore, the AIEAS-loaded HNTs were incorporated into poly(vinyl alcohol)/starch composites (PVA/ST) to prepare a dual delivery system for AIEAS. The AIEAS that were loaded in HNTs exhibited a significantly reduced release rate when passing through the soil layer of PVT/ST film, in comparison to the AIEAS that were not bound to HNTs. Following ten cycles of immersion in water, the PVA/ST film containing HNTs-AIEAS exhibited a total release quantity of AIEAS of merely 31.7%, in contrast to the PVA/ST film containing free AIEAS, which demonstrated a release quantity of 61.3%. Tensile tests were conducted to evaluate the stability of the leached film. The results indicated that the tensile strength of both PVA/ST/AIEAS and PVA/ST/HNTs-AIEAS films decreases continuously as the leaching number increases.

Kiselev et al. (2021) have developed environmentally friendly slow-release pesticide formulations using a biodegradable matrix made of poly-3-hydroxybutyrate and natural materials like peat, clay, and wood flour. These formulations have been infused with various pesticides, such as metribuzin, tribenuron-methyl, fenoxaprop-P-ethyl, azoxystrobin, epoxiconazole, and tebuconazole. Research shows that these formulations have sustained efficacy for up to 90 days. Polyhydroxyalkanoates (PHA) have gained interest as a promising material for drug delivery systems. The degradation rate is correlated with the physical form and the concentration of the active ingredient. Tablets with 10% metribuzin experienced a degradation period lasting over 60 days, with microparticles showing the highest rate of degradation. Fillers are incorporated to minimize costs and impact the hydrophilic-hydrophobic equilibrium and relaxation mechanisms within the polymer matrix, affecting the active substance's outflow kinetics and contributing to formulation degradation. Table 2 presents the properties of biodegradable composites used for the controlled release of herbicides and pesticides.

Table 2
Properties of biodegradable composites for controlled release herbicides and pesticides

Filler	Matrix	Agrochemicals	Properties	References
Bentonite clay	Gum acacia, gum tragacanth, rosin, ethyl cellulose, hydroxyethyl cellulose, Polyethylene methacrylate, methylcellulose, Polyvinyl acetate, Polyvinyl pyrrolidone	Azadirachtin-A	The duration of 50% discharge of azadirachtin-A into aqueous solution varied between 8.02–21.36 h. The half-life of the substance in the seed coats varies between 4.37–11.22 months. Polyethyl methacrylate, polyvinyl acetate, and polyvinyl pyrrolidone exhibited a higher degree of superiority compared to the remaining polymers	Nisar et al., 2009
Bentonite, kaolinite, fuller's earth	Polyvinyl chloride, carboxymethyl cellulose	Insecticide-Cartap hydrochloride	Catrap hydrochloride, sodium carboxymethyl cellulose and kaolinite exhibited exceptional efficacy (3.33%) in managing rice leaf folder in rice cultivated in open fields	Kumar et al., 2010
Sodium montmorillonite and alginate	Polyvinyl alcohol/starch composite	2,4-Dichlorophenoxyacetic acid	The release rate was reduced, maintaining the release of herbicide for a longer period. Possesses good mechanical and thermal properties	Wang et al., 2017
Montmorillonite (MMT)	Starch gel	Amethyne	Nanocomposites retained more herbicide than the pure samples. MMT addition retarded the starch and ametryne biodegradation.	Giroto et al., 2014
Chitosan	Polylactide	Imidacloprid	The submicron particles can prolong the pesticide release time owing to the amphiphilic structure of the copolymer	Li et al., 2011
Halloysite nanotubes	Polyvinyl alcohol/starch composites	Botanical herbicide -active ingredient of Eupatorium adenophora Spreng (AIEAS)	The AIEAS loaded in HNTs showed much slower release from PVT/ST film through the soil layer than free AIEAS. The tensile strength of the composite is higher than that of the non-composite polymers	Zeng et al., 2019
Peat, clay, wood flour	Poly-3-hydroxybutyrate	Metribuzin, tribenuron-methyl, fenoxaprop-P-ethyl, azoxystrobin, epoxiconazole, tebuconazole	Fillers reduce pesticide formulation costs by affecting hydrophilic-hydrophobic balance and relaxation processes, affecting active substance outflow and causing degradation	Kiselev et al., 2021

BIODEGRADABLE COMPOSITES FOR MULCHES

Plastic mulch, first discovered in the 1950s (Kasirajan & Ngouajio, 2012), increases soil temperature and alters crop microclimate (Tarara, 2000), protecting crops from weather, insects, and birds. It has been used in agriculture since its development in developed countries and is now spreading to developing countries. It has led to significant yield increases in vegetable production, particularly for tomatoes, peppers, eggplants, watermelons, muskmelons, cucumbers, and squash. Reflective mulch has been found to increase soluble solids content, total phenolics, flavonoids, and anthocyanins in Ontario wine grapes (Coventry et al., 2005), increase soluble solids in plums (Kim et al., 2008), and alter the anthocyanins content in butterbean (Kasperbauer & Loughrin, 2004). Strawberries ripened over red plastic mulch have higher aroma and flavor compounds.

Plastic mulches offer varying levels of weed control depending on the amount of light allowed through the mulch. Studies show that weed appearance decreases by 64-98% during the growth season. Additionally, reflective plastic mulch can protect crops against insect pests and diseases, similar to imidacloprid treatment. However, interference with visual cues by insects can cause increased attraction or repulsion to plastic mulched fields and crops.

Mulch films made from petroleum-based plastics, such as polyethylene, pose significant waste disposal issues and environmental pollution (Kasirajan & Ngouajio, 2012). The growing production of commercial polymers, particularly in agriculture and packaging, has raised concerns about long-term environmental accumulation and pollution (Albertsson et al., 1987). The removal of plastic is time-consuming (about 16 h/ha) and requires manual labor (Kasirajan & Ngouajio, 2012), with residual film in the field potentially affecting crop root development. The lack of biodegradability of these polymers has raised concerns about the long-term environmental effects of these plastics (Albertsson et al., 1987).

The incorporation of fillers into biodegradable matrices as a non-continuous phase has been observed to result in the formation of a complex structure, as reported by Khalil et al. (2019). According to Fowler et al. (2006), the combination of reinforcements and matrix yields a biomaterial that exhibits enhanced properties when compared to those of the individual components. In recent years, there has been a growing interest among the scientific community in biodegradable thermoplastics as a means to attain the parameters of polyethylene (PE) mulch films through the use of bio-composite materials (Sander, 2019).

According to Briassoulis (2006), biodegradable mulch films (BDMs) should exhibit suitable mechanical properties at the installation stage, such as tensile strength and elongation at break. Additionally, these mechanical properties should be maintained throughout the useful lifespan of the biodegradable mulches. Lastly, BDMs must be completely biodegradable in the soil before the commencement of the next crop season. The property of water vapor permeability (WVP) is crucial for mulching applications,

especially in dry regions, in addition to mechanical characteristics and biodegradability. Obtaining a comparable PE water vapor barrier value is imperative.

After reinforcements have been added, the material's strength and durability may be gauged by testing its mechanical characteristics. It is essential for mulching applications that bio-composites keep their shape under certain pressures and can still spread out and cover the soil (Yang et al., 2020). Three characteristics commonly reported and/or tested to provide insight into the mechanical properties of bio-based materials are tensile strength, elongation at break, and Young's modulus. All of them feature the following information: The tensile strength may be used to determine the durability of a material, while the elongation at break can reveal its pliability, elasticity, and ductility, and Young's modulus can reveal its rigidity (Khalil et al., 2019).

According to Merino et al. (2018), starch is one of the most commonly utilized agro-polymers for the production of cost-effective and biodegradable thermoplastic films. Starch-based biodegradable mulch films can be utilized in two distinct ways: either as a biodegradable reinforcement or as a biodegradable matrix. This polysaccharide serves as the fundamental component for both applications.

Starch was used as an organic filler in poly(vinyl alcohol) (PVA) films by Chiellini et al. (2001) and poly(butylene succinate) (PBS) films by Flores et al. (2009). Chiellini et al. (2001) made PVA-based bio-composite films from starch and sugarcane, apple and orange waste and apple fibers. These authors cast biodegradable films and examined the mechanical characteristics of starch content from 0 to 25% wt%. By adding 25% wt% starch content to PVA/orange and PVA/apple pomace fiber bio-composites, elongation at break values drop from 105.4 and 149.7% without filler to 29.6 and 65%, respectively. Tensile strength improved somewhat for PVA/sugarcane bagasse fibers with 25 wt% starch, which doubled their tensile strength values.

Flores and colleagues created bio-composite films using PBS and starch filler through a hot-pressing technique (Flores et al., 2009). The mechanical characteristics of the composite films were analyzed while altering the starch content, which included concentrations of 0, 20, 40, and 60 weight percent. The authors have reported a decrease in tensile strength values with an increase in starch content (0 wt% and 60 wt%), from 37.2 MPa to 5.7 MPa. A minor improvement in elongation at break was observed upon the integration of a decreased quantity of starch. Nevertheless, this particular parameter exhibited a decline upon the inclusion of contents exceeding 20% weight.

Both studies found that adding organic fillers enhances tensile strength qualities till a specific weight content due to the homogeneous dispersion of starch fillers into PBS and PVA and the matrix. According to their findings, the incorporation of plasticizers resulted in a rise in the elongation at break values in comparison to films that were not plasticized. However, the authors observed significant reductions in tensile strength. Plasticized and

suitable biopolymers are needed to employ starch as a biodegradable matrix (Briassoulis, 2004). Starch matrix-based biodegradable mulch films with organic reinforcements had superior mechanical characteristics compared to those of the polysaccharide matrix alone (Khalil et al., 2019).

Patil and Netravali (2016) introduced Kraft pulp microfibrillated cellulose into a mango seed starch matrix. In the production of biodegradable films, an environmentally friendly cross-linker was employed. To enhance the interfacial bonding in bio-composites, the chemical similarity between the matrix and fillers was utilized. Microfibrillated cellulose in mango seed starch matrix increased tensile strength and Young's modulus. Fillers loaded from 0% to 40% enhanced Young's modulus from 1.347 to 2.407 GPa. Patil and Netravali (2016) found that bio-composite films with informed filler dispersion and cellulose reinforcement had outstanding mechanical characteristics.

Spiridon et al. (2011) used maize starch as a matrix and microparticles from chemically modified starch as reinforcements to create bio-composite films. They added boost and beech lignin to chemically modified corn starch and starch microparticles. Lignin lowered Young's modulus and elongation at break but enhanced tensile strength. When compared to the original films, starch-beech and starch-boost lignin bio-composites have a higher degree of rigidity. Tensile strength rose by over 47% and 21%, Young's modulus fell by 8% and 31%, and elongation at break decreased by almost 39% and 30%. The explanation for this mechanical behavior was that strong intermolecular hydrogen bonds between the lignin and the starch caused the generation of compact structures.

In addition, Stasi et al. (2020) employed carbon ashes sourced from agricultural waste rich in lignocellulose to augment the mechanical characteristics of the thermoplastic maize starch matrix. The present study investigated the impact of carbon ashes on the mechanical behavior of thermoplastic maize starch. The findings revealed that the incorporation of carbon ashes resulted in a 15% rise in Young's modulus, a decline in elongation at break from 0.66 to 0.33, and a 14% reduction in the value of tensile strength.

The study conducted by Ayu et al. (2020) investigated the utilization of modified tapioca starch and polybutylene succinate (PBS) as a biodegradable matrix for bio-composite films. The said matrix was reinforced with empty fruit bunch fibers. In this study, biodegradable films were created using a consistent combination of PBS and modified tapioca starch. The volume fractions of fibers were altered to observe their effects. The incorporation of higher amounts of empty fruit bunch fiber content resulted in a notable decrease in both Young's modulus and tensile strength values, with reductions of 28% and 37%, respectively, observed at a fiber content of 50 wt%. The authors elucidated the matrix and fiber interactions through the lens of inadequate interfacial adhesion, disparities in functional groups, and non-uniform filler dispersion.

The study conducted by Finkenstadt and Tisserat (2010) aimed to assess the properties of biocomposite films of poly(lactic acid) (PLA) containing Osage orange wood fibers with varying particle sizes and weight percentages of 0, 10, and 25 wt%. Overall, the utilization of PLA/Osage orange wood fibers in the production of biodegradable mulch films resulted in marginal enhancements in terms of Young's modulus values at 25 wt% in comparison to pure PLA. In contrast, the elongation at break and tensile strength values exhibited a decrease when Osage wood fibers with a size of 400 nm and a weight percentage of 25 were employed; specifically, the elongation at break decreased from 18.7% to 8%, and the tensile strength decreased from 57.3 MPa to 36.6 MPa.

Merino and Alvarez (2020) investigated the use of natural seaweed microparticles as fillers in a thermoplastic starch blend matrix for the production of biodegradable mulch films. The incorporation of a low filler content resulted in enhancements in elongation at break, while the bio-composites Young's modulus increased. The addition of 10 weight percent of filler resulted in a decrease in the value of Young's modulus. According to the authors, the trend observed in Young's modulus can be attributed to the favorable adhesion and chemical compatibility between the matrix and seaweed microparticles. Discontinuities may arise at elevated levels of filler content, and the elongation during break behavior can also be impacted. Table 3 summarizes the mechanical properties of biodegradable composites used in mulches.

A novel agricultural mulch film, which is extremely stretchy, biodegradable, and entirely biobased, has been developed by Merino et al. (2022) at a price comparable to LDPE (Figure 5). They combine amorphous polylactic acid (PLA), 10 wt% epoxidized soybean oil methyl ester (ESOME), and inedible vegetable leftovers as fillers at various ratios to create composite materials for biodegradable mulches. The biodegradability of the films was found to be greatly impacted by the type of vegetable waste used as a filler. For instance, following 6 months of a soil burial experiment, PLA composites' biodegradability in soil rose from 0 to 38 wt% when films made with 20 wt% of spinach stems were used. The results also demonstrated that, depending on the type and quantity of vegetable waste added, proper PLA plasticization and vegetable waste addition can produce mulching-ready film with tensile strengths in the 10–24 MPa range and elongation at break values up to 460%.

The biodegradability of polysaccharides can be attributed to the presence of numerous hydrophilic polar functional groups in their polymeric chain. The biodegradability of polysaccharides in composite materials is altered when they are used as fillers or in the matrix. This affects the biodegradability of bio-composite films, which is influenced by factors such as chemical structure (Garrison et al., 2016), crosslinking density (Garrison et al., 2016), the nature of the components, and soil conditions.

Table 3
The mechanical properties of biodegradable composites for mulches

Filler	Matrix	Properties	References
Starch and sugarcane, apple fibers and orange waste	Polyvinyl alcohol	By adding 25% wt% starch content to PVA/orange and PVA/apple pomace fiber bio-composites, elongation at break values drop from 105.4% and 149.7% without filler to 29.6% and 65%, respectively. Tensile strength improved somewhat for PVA/sugarcane bagasse fibers with 25 wt% starch, which doubled their tensile strength values.	Chiellini et al., 2001
Starch	Poly(butylene succinate) (PBS)	Increasing starch content led to a decrease in tensile strength values from 37.2 MPa to 5.7 MPa, with a minor improvement in elongation at break but a decline in the parameter with higher starch content.	Flores et al., 2009
Kraft pulp microfibrillated cellulose	Mango seed starch matrix	Microfibrillated cellulose in mango seed starch matrix increased tensile strength and Young's modulus. Fillers loaded from 0% to 40% enhanced Young's modulus from 1.347 to 2.407 GPa.	Patil & Netravali, 2016
Microparticles from chemically modified starch	Maize starch	Tensile strength rose by over 47% and 21%, Young's modulus fell by 8% and 31%, and elongation at break decreased by almost 39% and 30%.	Spiridon et al., 2011
Agricultural waste carbon ashes	Maize starch	The addition of carbon ashes led to a 15% increase in Young's modulus, a decrease in elongation at break from 0.66 to 0.33, and a 14% reduction in tensile strength.	Stasi et al., 2020
Empty fruit bunch fibers	Tapioca starch and polybutylene succinate (PBS)	The addition of empty fruit bunch fiber significantly reduced Young's modulus and tensile strength values by 28% and 37% at a fiber content of 50 wt%.	Ayu et al., 2020

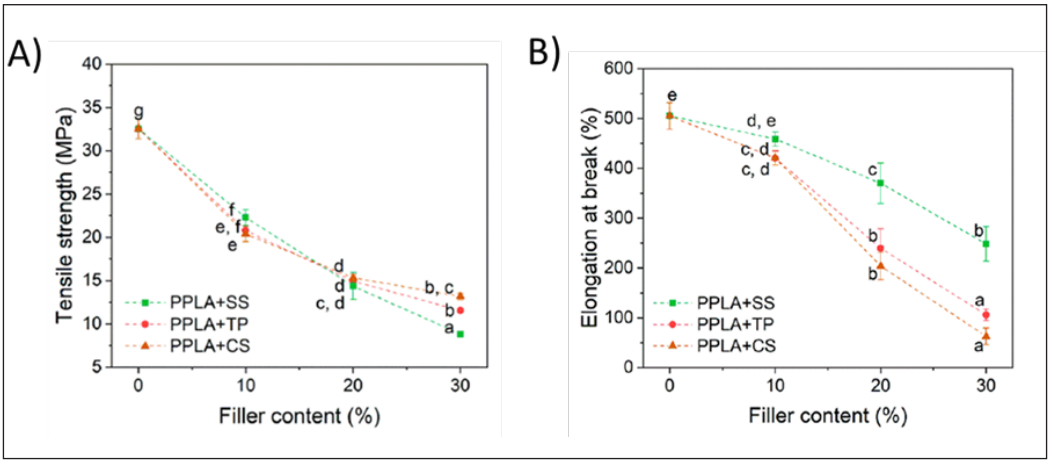

Figure 5. A) Tensile strength (MPa) and B) Elongation at break (%) of PPLA and its composites with 10, 20, and 30 wt% spinach stems (SS), tomato pomace (TP), or cocoa shells (CS). PPLA is the plasticized PLA with 10 wt% ESOME (Merino et al., 2022)

In the past, initial investigations into the biodegradability of biocomposite-based biodegradable mulch films centered on the assessment of mineralization tests conducted by soil microorganisms. Corti et al. (2002), Imam et al. (2005), and Chiellini et al. (2008) are examples of cases that have been studied. The authors incorporated blended polysaccharides or polysaccharide fillers into their research to augment the rate of biodegradability of PVA. Polyvinyl alcohol (PVA) is a vinyl polymer that comprises oxidizable functional groups within its polymeric chain. According to Briassoulis' (2004) report, secondary alcohol peroxidases isolated from soil have demonstrated the ability to effectively biodegrade PVA, indicating its high biodegradability.

The research carried out by Corti et al. (2002) sought to examine the influence of incorporating sugar cane bagasse, a naturally occurring filler, into the PVA matrix on the biodegradability of biocomposites. According to the authors' study, after an incubation period of 160 days, the mineralization of PVA containing 50 wt% sugar cane achieved a plateau of around 23.7%. The incorporation of a hydrophilic organic filler into the PVA matrix is responsible for the significant two-fold increase in mineralization of PVA film shown by the aforementioned value.

Imam et al. (2005) fabricated bio-composites utilizing PVA and PVA with lignocellulosic fibers that were strengthened with maize starch. The researchers then conducted a comparative analysis of the biodegradability of these composites over a 120-day period while they were exposed to prevailing environmental conditions in the soil. Following 90 days, the bio-composite films exhibited a notable decrease in both their dimensions and overall mass. In relation to the PVA composite filled with corn starch, it was observed that the film experienced a weight loss of around 51% from its original weight. Conversely, the

PVA/lignocellulosic fiber film filled with corn starch exhibited a weight reduction of 41%. One possible explanation for the discrepancy between the bio-composite films is that the PVA/lignocellulosic film, which features stronger crosslinking, degrades at a slower rate.

In contemporary times, there has been a growing interest in exploring alternative biopolymers as matrices or reinforcements to assess their biodegradability. Examples of such biopolymers include kenaf fibers (Pua et al., 2013), PBAT (Wang et al., 2015), chitosan (Arrieta et al., 2016), cotton fibers (Tan et al., 2016) and carnauba wax (Oliveira et al., 2019).

Pua et al. (2013) created citric acid and NaOH-modified kenaf/PVA composite films with different fiber concentrations. The weight of these bio-composite films was measured 15 days before and after a soil burial test to determine their biodegradability. The films became fragile, brittle, and weightless after being buried in the soil. Fiber loading worsened citric acid and NaOH-modified kenaf with PVA films. PVA film without fibers lost less weight (1.6%) than kenaf PVA bio-composites after 15 days. The biggest weight loss was 8.9% with 15 wt% citric acid-modified kenaf with PVA, followed by 7.73% with 5 wt% NaOH. The significant degradability of kenaf fibers is explained by the fact that all samples lost more weight than the pristine PVA film.

Moreover, Tan et al. (2016) fabricated mulch films composed of biodegradable polymers and natural fibers, as reported in their study. The biodegradable composites were made of cotton fiber combined with starch and cotton fiber combined with PVA, with a loading of biodegradable polymer equal to 16 wt%. The process of biodegradation was examined through laboratory and field-based soil burial tests. After 45 days, the cotton fiber/PVA composite exhibited a weight loss of approximately 54% due to biodegradation. The findings of both laboratory and field tests suggest that cotton fiber with starch has the potential to serve as a viable option for crops with abbreviated growth cycles, owing to its rapid rate of decomposition in soil.

The impact of incorporating small quantities of chitosan on the disintegration characteristic of the PLA/PHB matrix was investigated by Arrieta et al. (2016). The study examined three distinct biocomposites with the aim of producing electrospun mats that are both flexible and degradable, utilizing PLA-PHB as the base material. The biocomposites were composed of varying amounts of chitosan, specifically 0, 1, and 5 wt%. The researchers investigated the biodegradability of the films under composting conditions at a laboratory scale over 37 days. Their findings indicated that all biocomposite films underwent disintegration. The researchers arrived at the conclusion that the incorporation of chitosan, an organic filler, led to an augmentation in the rate of disintegration.

The addition of polysaccharide fillers has been observed to enhance the biodegradation rates of PVA-based mulches. According to Imam et al. (2005), mulch films that were fortified with 20% starch demonstrated a biodegradation rate of almost 50% after three

months. Similarly, Chiellini et al. (2008) found that mulches composed of PVA as a matrix and green algae with corn starch as fillers also exhibited a biodegradation rate of nearly 50%. Regrettably, all of the PVA mulch films under investigation failed to attain complete biodegradation. The biodegradation rates of PBAT-based mulches are affected differently by the inclusion of polysaccharides. According to a study conducted by Wang et al. (2015), there is a positive correlation between the starch content of mulches and their weight loss. Conversely, Oliveira et al. (2019) found that mulches with a 5% sugar cane content retained more weight than those with a 2.5% content. However, this trend was altered upon the inclusion of carnauba wax.

In summary, based on the findings, it appears crucial and obligatory to adhere to crop schedules. To adhere to the process of biodegradation, it is possible to alter the biodegradability rates of polysaccharide-based biodegradable mulch film by incorporating organic fillers and/or additives. It is recommended that endeavors be undertaken to conduct biodegradation analyses that compare various biocomposite biodegradable mulch films featuring distinct organic filler contents over an extended period.

BIODEGRADABLE COMPOSITES FOR CONTROLLED-RELEASE FERTILIZER

The implementation of controlled-release fertilizer in agricultural settings has emerged as a viable strategy for promoting long-term sustainability and safeguarding the environment. According to Liu et al. (2020), controlled-release fertilizers offer a regulated supply of nutrients to plants for a predetermined duration, thereby minimizing the loss of fertilizers into the soil. The utilization of controlled-release fertilizers (CRFs) has been the subject of significant research efforts aimed at delivering nutrients to the intended target in a more secure, cost-effective, and efficient manner. CRFs are designed to release nutrients at a desired concentration level and rate, thereby prolonging their availability in the soil. The application of this technique results in an enhancement of nutrient use efficiency (NUE) due to reduced frequency of dosing, as well as a decrease in environmental hazards by mitigating the rate of nutrient removal from the soil through precipitation or irrigation, as noted by Lawrencia et al. (2021). In contemporary times, the academic community has directed its attention towards composite technologies as a means to enhance the properties of controlled-release fertilizers. The term "composite material" refers to a combination of two or more materials that results in a final product possessing properties that surpass those of the individual constituent materials. In contemporary discourse, composite materials are frequently referred to as reinforcement arrangements or fillers that are incorporated within a matrix. According to Hsissou et al. (2021), the matrix is responsible for maintaining the coherence and alignment of the load.

The use of modern adsorbents, such as bentonite nanoclays, montmorillonite (MMT), zeolite, and halloysite, is prevalent in the production of coating materials. This is because of their exceptional cation exchange properties, as noted by Dubey and Mailapalli (2019). The use of nonionic polymers to modify the surface of clays like bentonite and MMT has become a popular method for enhancing the properties of polymers. This is due to the unique characteristics of these clays, including their mechanical and thermal properties, as well as their ability to absorb water. This information is supported by a study conducted by Zhao et al. (2018). The cost-effective and eco-friendly Montmorillonite (MMT) is a type of nanomaterial. According to Abdel-Wahhab et al. (2015), MMT is classified as a 2:1 type silicate within the structural family. This type of silicate consists of a layer of aluminum oxide dioctahedral that is situated between two layers of silicon oxytetrahedron.

Several investigations have been conducted using bentonite and montmorillonite as additives in polymer coatings to regulate the release of fertilizers (Bortolin et al., 2013; Liao et al., 2021; Sarkar et al., 2021; Ying et al., 2012; Zhao et al., 2018). Zhao et al. (2018) conducted a study wherein bentonite was subjected to modification through intercalation of polyethylene glycol within the interlayer space. The modified bentonite was then utilized in the preparation of polyurethane using in-situ polymerization with bentonite/isocyanate and soybean oil-based polyols. The resulting polyurethane was utilized as a coating for urea granules to reduce the rate of nitrogen release. Compared to pure PU, there has been a 27.5% increase in tensile strength and a 68% increase in breaking elongation. The coated PU-5%-bentonite composites exhibited a release duration of 74 days, as per the findings. Sarkar et al. (2021) developed biodegradable encapsulating films by blending clay and polymeric materials (starch/PVA). The clay used in the study was obtained from economically viable bentonite fractions. The encapsulating films were utilized for the production of diammonium phosphate (DAP) that was encapsulated within the CPSBs. The findings indicate that an increase in bentonite content (0–20 wt%) led to a reduction in both porosity and water absorption. The Korsmeyer-Peppas model was found to be a suitable fit for the release of nitrogen (N) and phosphorus (P) data obtained from the fertilizer. An increased proportion of bentonite in the composition of controlled-release fertilizers has been found to enhance structural stability and decrease the release of nitrogen and phosphorus from diammonium phosphate.

The study conducted by Ying et al. (2012) involved modifying urea-formaldehyde (UF) resins with montmorillonite (MMT) to create coating materials for controlled-release fertilizers. The addition of MMT to UF resins results in improved mechanical properties. The addition of 3% MMT to modified UF resin results in a significant increase in shear strength, with a nearly 20% improvement observed. The maximum shear strength is achieved under these conditions. The study reveals that the urea permeation rate of UF resin membranes that have been modified is inversely proportional to the thickness of

the membrane, while it is directly proportional to the content of MMT. Qu et al. (2015) conducted a study on the modification of urea-formaldehyde (UF) resins using soy protein isolates (HSPI) through copolymerization. The researchers aimed to investigate the impact of HSPI on the biodegradability of UF resins. According to Qu et al. (2015), the addition of HSPI with a lower hydrolysis degree to the system resulted in an accelerated rate of degradation.

Liao et al. (2021) incorporated MMT into a coating made of starch-based polyurethane (SPU) to enhance the regulation of nutrient release. The utilization of dodecyl dihydroxyethyl methyl ammonium chloride (DDMAC) as a cation exchange agent has been implemented to alter the properties of MMT. This modification is anticipated to enhance the hydrophobicity and dispersibility of MMT in SPU. The findings indicate that the dispersion of MMT particles within the SPU matrix was effective, resulting in an SPU/MMT composite coating that exhibited a denser and more resilient morphology with reduced visible porosity in comparison to SPU coatings. The increase in MMT content to 3% resulted in a prolonged duration of 49 days for the release of 75% nitrogen, which is significantly longer than the 14 days observed with SPU coating.

Wu et al. (2007) have prepared the encapsulation of Phosphate-solubilizing bacteria (PSB) cells in biodegradable capsules using PCL as the core matrix material and clay and starch as fillers to modify their physical properties, including permeability, biodegradability, and mechanical strength. Capsules are formulated to address challenges encountered in the practical application of bacterial cells as fertilizers. The system is designed to safeguard the cells while also enabling their gradual release into the soil in a manageable fashion. The findings indicate that PSB effectively decomposed all the cell-encapsulated capsules composed of PCL and PCL composites, leading to a sustained release of cells. The biodegradability of the capsules was observed to increase with the inclusion of starch, while the composites blended with clay exhibited lower biodegradability. The quantity and velocity of cell discharge from capsules made of PCL and encapsulated in cells were found to be directly proportional to the level of biodegradability and inversely proportional to the reduction in mechanical strength. However, the manner in which cells were released exhibited a high degree of similarity across all varieties of capsules.

In a study conducted by Harmaen et al. (2015), a slow-release fertilizer was created through the utilization of the extrusion technique. This was achieved by blending granular NPK fertilizer and empty fruit bunch (EFB) fibers. The thermal stability of BpF (bioplastic fertilizer) composites was found to be enhanced by the synergistic effect of PLA and EFB fibers. A homogenous blend of BpF was observed through the use of a scanning electron microscope (SEM). The biodegradation process resulted in a greater percentage of weight loss for fertilizers containing PLA and EFB fibers, primarily attributed to the inclusion of EFB fibers. Specifically, the weight loss percentages were 64.3% and 76.3%, respectively. In the course of the soil burial experiment, the fertilizer exhibited swelling and subsequently

permeated the tea bag. The degradation and solubility of fertilizer were impacted by factors such as temperature, moisture content, and soil water content.

Melaj et al. (2019) developed biodegradable polymer blends based on hydroxypropyl methylcellulose (HPMC) and chitosan to improve mechanical properties for coating tablets and granules. HMPC film has short soil durability, disappearing within 8 days. Chitosan films have more permanence, lasting 85 days in soil. The addition of chitosan to HPMC results in a longer-lasting film with a durability of 78 days, as compared to HPMC alone. Samples tested under conditions of higher relative humidity (76% RH) exhibited a decrease in Young's Modulus and resistance, whereas there was an increase in elongation at break. This may be due to synergistic or cumulative effects of plasticizers like glycerol, a low-molecular-weight, hygroscopic plasticizer that adds water to the polymer matrix.

In accordance with Ge et al. (2002) and Majeed et al. (2014), the incorporation of additives such as cellulose, starch and lignin has been found to improve the biodegradability of both natural and synthetic PC-CRFs. The biodegradability of synthetic materials was enhanced in mixed blends of starch/polysulfone (Tomaszewska & Jarosiewicz, 2004), starch/polyvinyl alcohol (PVA) (Han et al., 2009), starch/polyurethane (PU) (Ge et al., 2002) and ethyl cellulose (EC)/poly(3-hydroxybutyrate) PHB (Costa et al., 2013). Peng and Chen (2011) reported that the incorporation of lignin in a PU-based hydrogel resulted in an improvement in biodegradability. Conversely, the addition of PU chains to a lignin-based hydrogel was found to enhance its strength for coating ammonium sulfate. Singh and Sharma (2007) reported a degradation rate of 37% in polystyrene-g-starch samples after 160 days of incubation with soil media. The duration for which nutrients are released by fertilizers coated with lignin, cellulose, or starch is relatively brief, typically less than 30 days, as reported by Jamnongkan and Kaewpirom (2010) and Mulder et al. (2011). Polymer blends and composites derived from both natural and synthetic sources exhibit distinct differences in their biodegradation, which can be attributed to variations in microbial susceptibility, novel chemical linkages, and structural configuration.

THE CORRELATION EFFECT OF BIODEGRADABLE POLYMER COMPOSITES ON MECHANICAL AND BIODEGRADABLE PROPERTIES IN AGRICULTURAL APPLICATIONS

Biodegradable polymer composites have garnered significant attention in recent years due to their potential for sustainable and eco-friendly applications, particularly in the agricultural sector. These materials offer a promising solution to the environmental challenges posed by conventional petroleum-based plastics, which can have a detrimental impact on the environment (Chiellini et al., 2008).

The correlation between the mechanical and biodegradable properties of these composites is crucial, as it determines their suitability for various agricultural applications.

Nanofiller-reinforced biodegradable polymer composites, for instance, can exhibit enhanced mechanical properties while maintaining their biodegradability, making them suitable for use in mulches, controlled-release herbicides and pesticides, and controlled-release fertilizers (Sun et al., 2018).

Mulches, which are often used in agriculture to suppress weed growth, retain soil moisture, and moderate soil temperature, can benefit from the incorporation of biodegradable polymer composites. These composites can provide improved mechanical strength and durability, ensuring the mulch remains intact and effective for a longer period. Furthermore, the biodegradable nature of the composites ensures that they can eventually break down in the soil, minimizing environmental impact.

Controlled-release herbicides and pesticides are another area where biodegradable polymer composites can have a significant impact. These composites can be designed to gradually release the active ingredients, reducing the need for frequent application and minimizing the risk of environmental contamination. Similarly, controlled-release fertilizers can also be formulated using biodegradable polymer composites, allowing for a more efficient and sustainable delivery of nutrients to plants.

Recent studies have highlighted the potential of ternary blend system polybutylene adipate-co-terephthalate, polylactic acid, polypropylene carbonate and added lactic acid–isopropyl carbonate copolymer (PBAT/PLA-PPC-PTLA) polymer composites, to enhance the tensile strength, water vapor barrier properties and comparable biodegradation rate, making them suitable for a wide range of agricultural applications (Guo et al., 2024).

CONCLUSION

The incorporation of fillers, such as cellulose, agricultural waste, and diverse types of clay, has the potential to enhance the properties of biodegradable polymers that have been previously produced. The utilization of biodegradable polymers is advantageous for soil and microorganisms due to their capacity to mitigate the environmental impact of non-biodegradable plastics. Furthermore, the efficacy of these biodegradable polymers is comparable and commendable.

At the same time, it is imperative and mandatory to comply with crop schedules. In order to conform to the biodegradation process, it is feasible to modify the biodegradability rates of biodegradable mulch film through the integration of organic fillers and/or additives. It is advisable to initiate endeavors to carry out biodegradation assessments that juxtapose diverse bio-composite biodegradable mulch films that exhibit discrete organic filler concentrations for a prolonged duration. A thorough evaluation of fillers and matrices is imperative to satisfy the mechanical characteristics of plastic mulch and the controlled release requirements of herbicides, pesticides, and fertilizers.

Moreover, the correlation between the mechanical and biodegradable properties of polymer composites is crucial for their successful application in the agricultural sector. Biodegradable polymer composites, including nanofiller-reinforced systems, offer a sustainable solution for the development of mulches, controlled-release herbicides and pesticides, and controlled-release fertilizers, with the potential to address environmental concerns while maintaining the necessary functional properties.

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