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Sustainable packaging review: Recent materials and technology of smart biodegradable packaging

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ABSTRACT

Plastic is widely used as product packaging. The time-consuming degradation of old plastics leads to an increase in environmental pollution. Sustainable packaging has been recently developed to decrease the problem. Along with the need to identify product quality during storage and distribution, smart biodegradable packaging is developed. The packaging not only contains and protects the product but also provides information about the rapid change of product quality. This article reviews various smart biodegradable materials such as polymer, gelatin, chitosan, or starch materials and packaging production technologies such as extrusion, compression molding, and film casting technology. The latest innovations in smart packaging are labels that can sense and record changes in food products with unique signs on the packaging. This label can detect if there is a leak in the package; the indicator will show a change. The combination of materials according to utilize an abundance of natural resources of each country and affordable technology needs to be continuously developed to produce sustainable packaging that can be produced in many countries.

Keywords: sustainable packaging, smart, biodegradable

INTRODUCTION

Plastics are the primary material widely used as packaging that can cause many environmental problems. Based on data from IMEF (2020), Indonesia produced 34.5 million tons of waste/year, and 17% of waste is plastic. Plastic that has been modified to be part of sustainable packaging is not polluting the environment. Sustainable packaging (SP) is crucial because it reduces the ecological footprint of all the stages in the product's life cycle. It helps both the producer and the consumer reduce their environmental impact. SP was developed to reduce waste using environmentally friendly materials (Magnier et al., 2016), called biodegradable packaging (BP). Ambrose (2020), BP can be an alternative because microbes easily damage the material that constructs BP. BP material is mainly in the form of a biopolymer. Biopolymers can be extracted directly from biomass such as cellulose, lignin, chitin, chitosan, wheat gluten, gelatin, casein, and protein (Spizzirri et al., 2015). The biopolymer materials discussed in this review are chitosan, gelatin, and starch because the ingredients for these materials are easy to obtain. Potential ingredients for biopolymers in Indonesia are corn, sago, soybeans, potatoes, cassava, and chitin for making chitosan in crustacean shells. Based on data from the Indonesian Central Statistics Agency in 2018, corn production was 30 million tons, cassava 19 million tons, soybean 983 thousand tons, sago 460 thousand tons, and crustacean 916 thousand tons. Applications of BP manufacturing technology include extrusion, compression molding, and film casting. This technology has been widely utilized in industrial and laboratory-scale food and beverage packaging. The four main markets for BP are food packaging, non-food packaging, disposable personal medical devices, and consumer goods (Davis and Song, 2006). This review discusses the development of smart biodegradable packaging (SBP) in terms of materials and technology and opportunities for BP innovation research in many countries.

MATERIALS AND METHODS

This paper uses a systematic review approach as the primary method of collecting and analyzing the literature (Hariyati, 2010). This article presents the latest research results from various sources related to biodegradable materials and technology that offer information for researchers in many countries to develop sustainable packaging. Literature studies and surveys on quantitative and qualitative empirical studies have been published, such as journals, books, encyclopedias, and additional information from the Australian Packaging Covenant Organization (APCO). Journals, books, and encyclopedias can be accessed at the publishers: Elsevier, Emerald Insight, Springer, Google Scholar, and Taylor & Francis Group. The search used the keywords "sustainable packaging," "smart packaging," "biodegradable packaging," "biodegradable materials and technology," and "edible film." The Literature books from international publishers. Those publications were analyzed in the period 2006-2021.

RESULTS AND DISCUSSION

Sustainable Packaging

Packaging is an extrinsic element of a product that should be effective, efficient, cyclic, and safe (Deliya and Parmar, 2012). Packaging primarily accommodates and protects products from producers to end consumers, attracts consumers, and provides product information. SP has more function to protect the environmental impact than conventional packaging (APCO, 2020). Lewis (in Robertson, 2009), Australia's Sustainable Packaging Alliance (SPA), developed four principles related to SP:

a. Effective: The system applied in the packaging process adds real value to society effectively and protects the product throughout the supply chain.

b. Efficient: Packaging systems are designed to use materials and energy efficiency throughout the product life cycle.

c. Cyclic: Packaging materials can be recycled continuously through natural or industrial systems with minimal material degradation. Recovery rates must be optimized to ensure that they achieve energy savings and greenhouse gas emissions.

d. Safe: The packaging components in the system, including materials, inks used in packaging, pigments, and other additives, possess zero risks to humans or the ecosystem.

There are ten principles for consideration of packaging design and procurement to increase SP. There is recovery design, material efficiency, design to reduce waste, eliminate hazardous materials, use recycled materials, use renewable materials, plan to minimize litter, design for transport efficiency, design for accessibility, and provide consumer information on sustainability. Recoverability of packaging refers to the availability of systems for reuse, recycling, composting, or energy recovery. Optimized or material efficiency refers to no further reductions in packaging weight or volume are possible at present. Packaging design ensures products reach their final destination without any damage or wastage, and this includes information on the label to assist consumers in reducing waste. Eliminating hazardous materials means avoiding using hazardous substances that could be toxic to humans or their living organisms. Using recycled and renewable materials in packaging helps create sustainable markets because these materials generally use less energy and water to manufacture, cost savings, and have a lower environmental impact. Design of minimizing litter aims to design any package that tends to be found in the litter stream (such as fast food and beverage packaging) to reduce the likelihood of it becoming litter. Packaging should be designed to maximize transport efficiency through lightweight, fully utilizing shipping space where appropriate. Design for accessibility Relates to the ease of using consumer experiences when completing tasks, including factors such as ease of opening and readability of labels. Providing consumer information on sustainability means providing clear information or advice about any claims made about the packaging's appropriate disposal or environmental attributes (e.g., recycled content or sustainable sourcing of materials) on the packaging or packaged product (APCO, 2020).

Smart Biodegradable Packaging

Kerry and Butler (in Wang et al., 2019) state that smart packaging is defined as packaging that provides a functional level apart from protecting, loading, and providing product information. Smart packaging refers to packaging systems with embedded sensor technology used with foods, pharmaceuticals, and many other types of products. It is used to extend shelf life, monitor freshness, display information on quality, and improve product and customer safety (Schaefer and Cheung, 2018). Smart packaging's exact function has varied solutions and depends on the packaged products, for example, food, beverages, medicines or health products, and household products (Kuswandi et al., 2011). BP is from environmentally friendly materials to be easy to recycle, and BP is nontoxic, thereby reducing carbon emissions and climate change (Ambrose, 2020). According to Davis and Song (2006), there are two objectives for developing BP: utilizing renewable energy and potential sources of raw materials and facilitating integrated waste management to reduce waste.

Smart Biodegradable Materials

Chitosan, gelatin, and starch are part of the biopolymer because biodegradable materials are from renewable resources (Spizzirri et al., 2015).

Biopolymers serve as an alternative material for environmentally friendly packaging. The advantages of using biodegradable materials are reducing fossil-based raw materials to reduce carbon dioxide release, biological degradation and reduce landfills with the possibility of applying agricultural resources to produce environmentally friendly materials. The following subsections describe biopolymers, chitosan, gelatin, and starch.

Biopolymers

Biopolymers are environmentally friendly food packaging materials because they are easily biodegradable (Tang et al., 2012). Biopolymers are natural polymers materials, including starch, cellulose, chitosan, and gelatin, which can replace petroleum-based materials (Chen et al., 2019; Elsabee et al., 2013). Food packaging is generally made of natural biopolymers from starch, cellulose, chitosan, agar from carbohydrates and gelatin, gluten, alginate, whey protein, and collagen from protein (Stoica et al., 2020). The categories of biopolymers are shown in Figure 1. and applications for SBP as shown in Table 1.

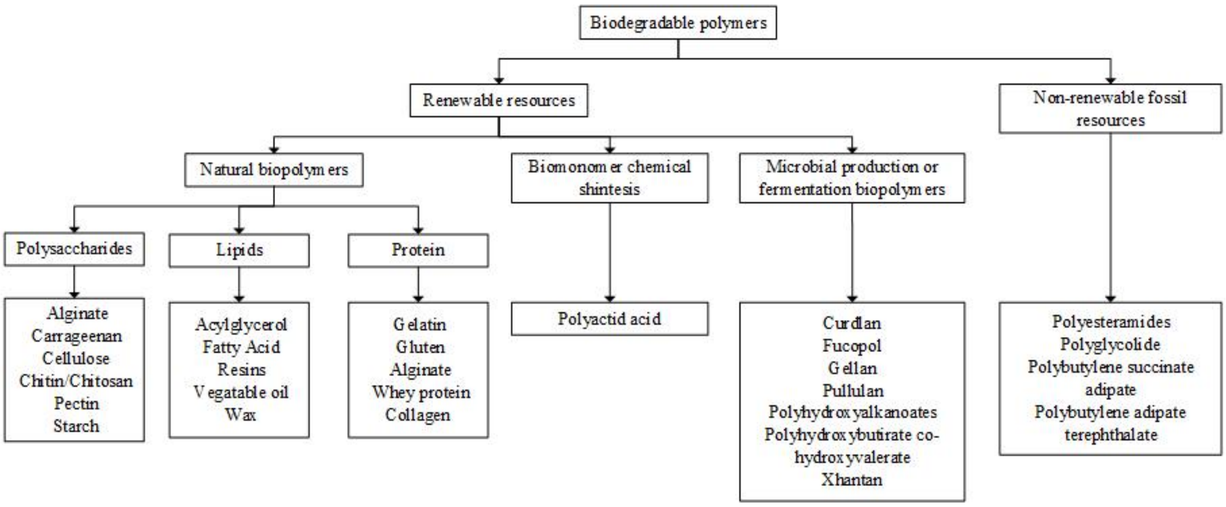

Figure 1. Biopolymer category (Adapted from Haghighi et al., 2020; Rhim et al., 2013).

Chitosan

Chitosan is a linear polysaccharide consisting of 1, 4 related glucosamine and N-acetylglucosamine. Chitosan is a natural polymer derived by the deacetylation of chitin in alkaline media (Kamkar et al., 2021), which is the second-largest polysaccharide in nature after cellulose (Giannakas et al., 2014). Chitosan has potential applications in food technology because it is biocompatible, nontoxic, decomposes in a short time, and can form a good film. Chitosan can improve mechanical, antifungal, and waterproof properties. The change in chitosan from 5% to 30% can preserve food for up to 15 days (Soltani et al., 2018). Chitosan composite film with kojic acid significantly decreased the viscosity, moisture content, water vapor permeability and increased the film's antibacterial activity (Liu et al., 2020). The biodegradable film was made by mixing guar gum, chitosan, and polyvinyl alcohol-containing mint and orange peel extract and cross-linked with nontoxic tetraethoxysilane (TEOS). Biodegradable films can degrade rapidly for six days, and it is confirmed that there is strong microbial activity in the soil (Bashir et al., 2017). The mass of film biodegradation decreases by 80% in 14 days, so that composites from chitosan have the potential to become environmentally friendly food packaging materials (Oberlintner et al., 2021; Muthmainna et al., 2019).

Table 1. Application chitosan, gelatin, starch as film.

Items	Material	Bioactive compounds	Parameter	Characteristic	Source
Chitosan	AgNO3, gelatin, polyethylene glycol, acetic acid	AgNPs (*Mimusops elengi* fruit extract)	Shelf life of fruit	Thickness: 87.60 ± 2.19 µm Tensile Strength: 21.19 ± 1.01 MPa Elongation at break: 27.23 ± 0.76 %	Kumar et al., 2018
	Polyactic acid, nanochitosan, polyvinyl alcohol, polyethylene glycol	PLA / NCS	Antimicrobial properties of films in cold conditions	Thickness: 0.075±0.02 mm Tensile Strength: 366.33 ± 0.12 Kg/cm^2	Fathima et al., 2018
	Cloisite-Na +, cloisite-Ca + 2, glacial acetic acid, glycerol and tween 80, water essential oil	Rosemary essential oil or ginger essential oil	Shelf life in cold conditions	Thickness: 40 to 70 µm	Pires et al., 2018
	Glacial acetic acid, hexadecyl-trimethylammoniumbromide and (CTAB)	Curcumin	Inhibition against *Staphylococcus aureus* and *Escherichia coli*	Thickness: 0.0931 ± 0.0021 mm Tensile Strength: 19.87 ± 1.02 MPa Elongation at break: 25.46 ± 2.16 % Water vapour permeability: 15.21 ± 1.83 g 10−11/sm^2 Pa	Wu et al., 2019
	Methylcellulose powder	Red barberry anthocyanins	pH-indicator and halochromic	Thickness: 0.130 ± 0.008 mm Tensile Strength: 45.05 ± 0.55 MPa Elongation at break: 16.05 ± 0.07 % Water vapour permeability: 2.35 ± 0.05 g 10−11/sm^2 Pa	Sani et al., 2021
Gelatin	Bovine gelatin, glycerol	Red cabbage	pH indicators	Thickness: 58.2 ± 5.9 µm Moisture content: 21.3 ± 0.6%	Musso et al., 2019
	Gelatin, glycerol	Cashew gum powder	Biodegradability assay	Thickness: 67 ± 0.02 mm Tensile Strength: 82.56 ± 0.06 MPa Elongation at break: 114.90 ± 24.54 % Water vapour permeability: 1.84 ± 0.13 g.mm.k.Pa^{-1} h^{-1}m^{-2}	Oliveira et al., 2018
	Starch, sorbitol	*Tetradenia riparia* extract	Antimicrobial activity and antioxidant activity	Thickness: 0.378 ± 0.010 mm Tensile Strength: 7.48 ± 0.283 MPa Elongation at break: 34.1 ± 0.598% Water vapour transmission rate: 11.3 ± 0.651 g h^{-1}m^{-2}	Friedrich et al., 2020
Starch	Cassava starch, glycerol	Green tea and basil	pH indicator, degraded in soil and thermal stable	Thickness: ~0.25 mm Water vapour transmission rate: 3.4 ± 0.2 g^{-10}s^{-1}m^{-1}Pa^{-1}	Medina-Jaramillo et al., 2017

Continued

Table 1 (Continued).

Items	Material	Bioactive compounds	Parameter	Characteristic	Source
	Starch, xanthan gum and glycerol	Sodium hypophosphite and citric acid	thermal and microstructural properties	Thickness: 430 ± 32 µm Tensile strength: 2.23 ± 0.24 MPa Strain at break: 99.49 ± 15.08 % Water vapour transmission rate: 2.0 $g^{-10}s^{-1}m^{-1}Pa^{-1}$	Simoes et al., 2020
	Brown rice starch, chitosan, glacial acetic acid, Refined, bleached and deodorized palm oil	-	Antiomicrobial and biodegradability	Thickness: 0.22 ± 0.022 mm Tensile Strength: 15.2 ± 0.432 Mpa Elongation: 34.7 ± 1.15 %	Hasan et al., 2020
	Cassava starch, chitosan, glycerol, distillated water	*Eugenia uniflora L.* leaf extract and / or natamycin	Physical properties, antioxidant and antifungal activities of films	Thickness: 0.080±0.004 mm Tensile Strength: 13.3±1.4 MPa Elongation at break: 2.8±0.7 % Water vapour transmission rate: 1.98±0.38 10^{-8} g.mm/h. cm2.Pa	Chakravartula et al., 2020

Gelatin

Gelatin is a protein resulting from partial hydrolysis of collagen at controlled temperature and pH (Leite et al., 2020). Gelatin has low barrier properties against moisture and poor mechanical strength, so adding natural additives such as pure compounds, essential oils, and plant extracts are necessary. Natural additives also function as antimicrobials and antioxidants in biopolymer films (Rhim and Kim, 2014). Gelatin-based film mixtures with different properties show that gelatin forms a great layer (Suderman et al., 2018). The cross-linking effect of phenolic and gelatin substances increases cross-linking of proteins with the concentration of oxidized phenolic compounds, resulting in a tighter and stiffer film structure (Choi et al., 2018). Gelatin film containing a synthetic acid-base indicator (methyl orange, neutral red, and green bromocresol) or natural (curcumin) has changed color when contacted with gaseous, liquid, and semi-solid media with different pHs. This serves as an indicator of change or food spoilage because there is a response to the growth and metabolism of microorganisms that evaporate during storage (Musso et al., 2016).

Starch

Starch is one of the natural biopolymers available in abundance, nontoxic, and forms films (Azevedo et al., 2017). Starch is formed into a thermoplastic substance with low mechanical properties, poor safety against oxygen and moisture content. The molecule consists of d-glucose polymers: amylose (20% –30%) and amylopectin (70 –80 %), depending on the source, and have different proportions (Rydz et al., 2018). Mixing composted polyester, polybutylene succinate, poly-caprolactone with starch less than 50% increases water resistance, improves mechanical properties, processing, and has biodegradation properties (Ahmadzadeh and Khaneghah, 2019). The main ingredients utilized in food packaging are mixed with starch due to components actively transmigrating (Ivankovic et al., 2017). In Indonesia, biodegradable plastics made from sago starch and cassava have considerable potential to be developed as environmentally friendly packaging materials (Kamsiati et al., 2017).

Smart Biodegradable Technology

Technology for creating plastic or edible films is multiple to support a sustainable environment. Some of the technologies used are extrusion, compression molding, and film casting. These technologies are efficient and fast for producing plastic packaging or edible film to be applied on an industrial or laboratory scale. The following subsections explain more about extrusion technology, compression molding, and film casting. The technology applications of extrusion, compression molding, and casting film are shown in Table 2.

Table 2. Application extrusion, compression molding, and casting film.

Technology Process	Application	Attribute	Source
Extrusion	Starch / PBAT nanocomposite films	Tensile strength: 7.4 Mpa Thickness: 40–50 µm	Zhai et al., 2020
	Poly (butylene succinate) biocomposites	Tensile strength: 78.1 Mpa Thickness: 1.8-2.1 mm	Zhao et al., 2020
	Starch-based nanocomposite films	Vertical tensile strength: 3.07 Mpa Horizontal tensile strength: 3.83 Mpa	Gao et al., 2019
	Starch / chitosan-based composites	Tensile strength: 0.6 ± 0.1 Mpa Thickness: 617 ± 29 µm	Llanos et al., 2021
	Active meat packaging from thermoplastic cassava 1starch-containing sappan and cinnamon herbal extracts	Tensile strength: 11 Mpa and 9 Mpa Thickness: 0.06 mm and 0.05 mm	Khumkomgool et al., 2020
	Cassava starch and anthocyanins	Tensile strength: 0.4 ± 0.0 Mpa Thickness: 1.5 ± 0.2 mm	Vedove et al., 2021
Compression molding	Active fish gelatin films with anthocyanins	Tensile strength: 41.3 ± 2.7 Mpa	Uranga et al., 2018
	Poly (3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) and Poly-thylenglycol	Tensile strength: 22 ± 3Mpa Thickness: 0.0025 mm	Requena et al., 2016
	PHBV / PBAT-based nanocomposite films with organically modified nanoclay	Tensile strength: 15.31 Mpa Thickness: 150–200 nm	Pal et al., 2020
	Edible Films Production from *Canavalia enciformis (L.)* Flour	Tensile strength: 4.091 Mpa Thickness: 0.302 mm	Lindriati and Arbiantara, 2011
Casting film	Kaolin (Kln) and silver-kaolin (Ag-Kln) in gelatin-composite films	Tensile strength: 3.51 ± 0.18 Mpa Thickness: 89.00 ± 1.00 µm	Najwa et al., 2020
	Poly-vinyl alcohol / starch / glycerol / citric acid composite films	Tensile strength: 14 MPa Mpa Thickness: 635 µm	Das et al., 2019
	Lindur fruit starch with addition of glycerol and carrageenan	Tensile strength: 132.88-168.33 kgf / cm^2 Thickness: 0.13-0.20 mm	Jacoeb et al., 2014

Extrusion

Extrusion is a technique in the field of materials science by applying it to starch films. The compression and extrusion technique is faster and more efficient so that it is suitable for the industrial-scale production of plastics. Using a thermo-mechanical process can accelerate output, reduce production time and costs, thereby increasing process effectiveness (Nilsuwan et al., 2019). Extrusion is done by a single screw extruder, as shown in Figure 2.

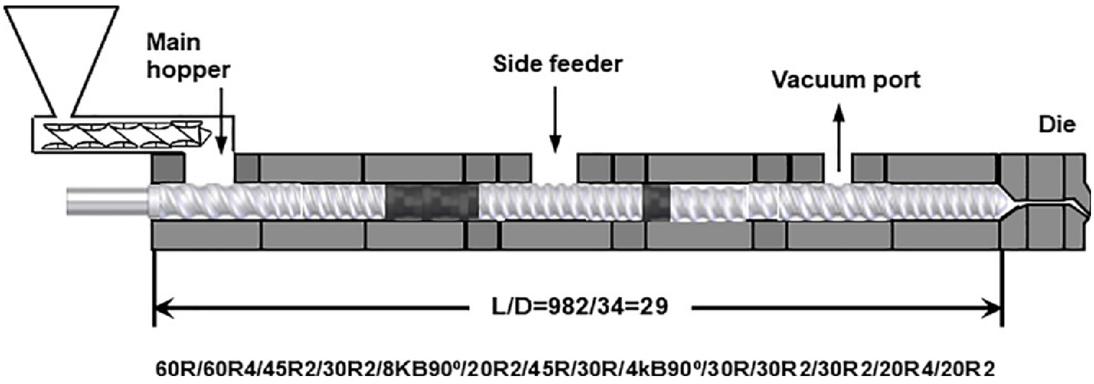

Figure 2. Cylindrical extruder with screw configuration (Torres-Giner et al., 2018).

The continuous process is advantageous because it uses high pressure and temperature. The extruder has a thread diameter of 27 mm and a length/diameter ratio of 48:1 (L/D) at a constant temperature at 180ºC with a screw speed and feed speed of 100 rpm and 5 kg/hour. Allows the extruder to have reactor-like properties, so that processing conditions depend on the characteristics of the polymer mixture, reactive extrusion (REx) can be achieved (Gutierrez et al., 2017; Gutiérrez and Alvarez, 2018). Pellets (90g/film) are then pressed using a hydraulic press at 130°C and 5 × 106 Pa (50 bar) for 10 minutes, after which a cooling cycle was performed before being applied to a temperature of 30°C. The resulting material was labeled, and the film was conditioned under controlled relative humidity (RH, 57%) for a week at 25°C (Julien et al., 2019).

Compression Molding

Compression molding is a plastic forming process that requires less space and time so that more efficient and continuous. Compression molding can be applied to edible films forming with pressure affecting thickness, color value, elongation, tensile strength, and WVTR (Lindriati and Arbiantara, 2011). Filming with compression molding techniques is prepared by the melt blending process and compression molding (Menzel, 2020). The ingredients are mixed for 15 minutes on a roll in the film-forming, which is previously heated at 55ºC until homogenous. It is pressed with compression at a temperature of 80ºC and 300 bar, obtained a rectangular sheet with an average thickness of 1.30 mm (Andonegi et al., 2020).

Casting Film

The casting method is widely used because it is the simplest method to create biopolymer films. The application of casting film to food products fulfills food safety, maintains quality, and increases shelf life (Priyadarshi and Rhim, 2020). Soltoni et al. (2018) showed that single-layer films were formed using the casting film technique. Chitosan was dissolved in 10 ml of 2 v/v% acetic acid solution under stirring to produce a transparent solution. The nanocellulose gel was dispersed in 20 ml deionized water and sonicated (200 W) during the resulting homogeneous dispersion. Then 3.99-10% of gelatin polymer is added to the solution. Previous treatment on gelatin is heated and stirred until dissolved. Subsequently, it was mixed at a temperature of 45ºC and ultrasonication (50W) for 2 minutes. The final solution was dried in an oven at 55ºC for 12 hours to form a film. In this method, protein or polysaccharides are dispersed in a mixture of water and plasticizer or hydrocolloids in starch, glucomannan, or carrageenan, and plasticizer.

CONCLUSIONS

Innovative biodegradable packaging (SBP) has a big role in protecting the environment. Naturally, biodegradable packaging is expected to be an integral part of life. SBP material sources include chitosan, gelatin, and starch. Many potential ingredients to be developed into biopolymers are corn, sago, soybeans, potatoes, cassava, and chitin in crustacean shells. Rapid technological developments, such as extrusion, compression molding, and film casting, can be utilized to produce SBP. It is crucial to introduce biodegradable polymer materials and technologies. SBP continues to grow, and the discovery of new, more effective technologies, integration between technologies, and production scale doubling up to be cheaper. The availability of materials according to natural resources and affordable technology can be utilized to produce SBP in the future.

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